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THE BIOLOGY AND POPULATION ECOLOGY OF DEEP-SEA RED CRABS, *CHACEON SPP.* IN THE NORTH ATLANTIC OCEAN

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THE BIOLOGY AND POPULATION ECOLOGY OF

DEEP-SEA RED CRABS, *CHACEON SPP.* IN

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BY

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ABSTRACT

Red crab (*Chaceon spp.*) fishery resources exist on both sides on the North Atlantic, and the fisheries that harvest these resources seek to maintain their sustainability. To be able to conduct fishery assessments with less uncertainty, resource managers need a better understanding of the life history characteristics of the species, more recent information on the abundance and distribution of the resource, and finally reliable estimates of the levels of exploitation and the effects of harvesting of the resources. This study contributes to the body of knowledge of the resource in the western Atlantic resource and red crab fishery off the Northeast US coast, and of the resource in the eastern Atlantic and emerging red crab fishery in the Cape Verde Islands off West Africa.

One aspect of this study assessed the characteristics of sea-sampled catches in the western and eastern Atlantic as indicators of population characteristics. In the western Atlantic, I investigated the past and current status of the population, changes in the size distribution of the red crab population due to fishing and the effects of discarding. I used data from a tagging study initiated in 2010 and 2004-2005 trawl survey by Dr. Richard Wahle of the University of Maine. I have supplemented these data with National Marine Fisheries Service trawl-survey data from 1974, and data that I collected in the summer of 2012 and 2013 aboard red crab commercial fishing vessels. In the eastern Atlantic, I used data collected during four exploratory fishing trips on a virgin resource located in the Cape Verde Islands.

In general, the life history characteristics of red crab resources are similar in the western and eastern Atlantic in terms of carapace width and size-frequency

distribution. Males are always larger than females. In the western Atlantic I found that there has been a size increase in the harvested male population between 2010 and 2012, and I hypothesize that this could be due to a decrease in fishing effort overall, or is a response to an effort to return the smaller males to the sea. I also documented that there is a discard mortality of male and female red crabs, but the level of this mortality is small, and interestingly, corresponds to a level reported by a previous researcher based on "hotel experiments." The fishery in the western Atlantic, although certified sustainable by the Marine Stewardship Council, experiences the effects of moderate fishing intensity on males, and is considered fully exploited. I observed a change in the selectivity of fishermen when sorting the red crab catch from the trap, as the discard probability function has become steeper and resembles a more knife-edge selection process. In the northern area, the proportion of total discards to landings decreased from 1.35 in 2002 to 0.27 in 2012, and females became the dominant portion of the discards. In the southern area, the proportion of total discards to landings decreased from 0.82 in 2010 to 0.10 in 2012, with females representing the dominant portion of the discards. The discard mortality study for females suggests that the fishing effects have been negligible on the female red crabs, as discard mortality is estimated to be minimal at 5%.

As for male red crab, the result of a length-based catch curve analysis (LCCA) indicates evidence of higher fishing mortality (F) in recent years (2012) for the northern area (F = 0.47) compared to the southern area (F = 0.20). Although this finding reflects the current fishery status, the estimated F value might be overestimated due to the more selective nature of trap surveys (the catch is aggregated toward the mean carapace width) and these values are valid only for the localized areas (600-800 meters) where the fishing operations occur. Although there has been concern regarding mating success of females due to lack of large males, I found no evidence to support this hypothesis. I found that the probability of successful mating in the logistic model increased as carapace width increased. I also made a comparison of mating success from the 1974 to the 2004-05 surveys for the southern area, and that indicates a higher probability of mating success in the more recent years.

I separated the red crab population in the northwest Atlantic into two sub-stocks, with Hudson Canyon as a bio-geographic barrier dividing the population along the upper continental slope off New England (north) and the mid-Atlantic (south), so as to be able to differentiate effects of fishing on the older mature fishery in the north and east from the newer fishery in the south. The results of a biomass dynamic model used to estimate maximum sustainable yield (MSY) found that the total MSY is estimated to be 1797 mt; this level is slightly higher than the current Total Allowable Landing (TAL) that was set at 1775 mt. The average fishing mortality in the northern area (0.13) was lower than that in the southern area (0.17), and both values are lower than the values estimated from the LCCA analysis. The F/F_{MSY} and B/B_{MSY} ratios from north and south areas indicate that the red crab resource is neither overfished nor is overfishing occurring in the most recent year (2012).

In the eastern Atlantic, I noted a low CPUE for red crabs in Cape Verde, and that indicates a low fishable biomass (377 MT). This estimated biomass will support a MSY of only 28 MT or 18% higher (with the addition of the area around Brava and

Fogo Islands) and this combined with the low CPUE will not support an economically viable and biologically sustainable fishery.

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PREFACE

The format for this dissertation was prepared in manuscript format according to the Graduate School of the University of Rhode Island. Three manuscripts address the study of deep-sea red crab on the continental slope of the northeast United States and one manuscript that assesses the potential for a red crab fishery in Cape Verde. The four manuscripts conform to the formatting of *Fisheries Research* journal and will be submitted for review upon completion of this dissertation.

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Manuscript-1

To be submitted to *Fisheries Research*

Trap performance and discarded catch in the deep-sea red crab fishery of the northwest Atlantic

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Trap performance and discarding in the deep-sea red crab fishery

of the Northwest Atlantic

ABSTRACT

The deep-sea red crab (*Chaceon quinquedens*) fishery was started in the 1970s, and has targeted male crabs only with discards of females and undersize males. Currently, no regulations limit the minimum legal size for red crabs, although fishermen have been using selective fishing gears and practices to capture mostly male crabs with a carapace width of larger than 105 mm. The conical traps used include an escape vent to allow for the release of smaller crabs, the traps are set in a specific depth range that maximizes the catch (600 - 900 m), and the traps are fished for one day to maximize catch rate and minimize trap saturation before the bait is consumed.

I evaluated the gear selectivity of the trap with different vent sizes and evaluated the current trap used in the fishery in relation to the soak time. The carapace width at 50 % retention probability (CW_{50}) values for the 9-, 10-, and 11-cm escape vents were estimated to be 90, 99, and 107 mm, respectively, although other factors result in a smaller mean size in the trap catch with increasing vent size. Increasing soak time resulted in a catch of larger crabs, but because there are so few large crabs in the stock, my findings suggest that the current gear used in the fishery (9 cm in vent size) is the best in retaining sufficient quantities of marketable red crabs. I observed a change in the selectivity of fishermen when sorting the red crab catch from the trap, as

the discard probability function has become steeper and resembles a more knife-edge selection process. In the northern area the proportion of total discards to landings diminished from 1.35 in 2002 to 0.27 in 2012, and females became the dominant portion of the discards. In the southern area, the proportion of total discards diminished from 0.82 in 2010 to 0.10 in 2012, with females representing the dominant portion of the discards. I also observed that discards are heavily affected by market demand; when there is a new market demanding other than the usual size range of crabs, there is be a change in fishermen behavior that affects the discards as well. The result from the discard mortality study for females in the northern part of the stock suggested that the fishing effects have been negligible on the female red crabs, as discard mortality is minimal at 5%.

1. Introduction

The deep-sea red crab (*Chaceon quinquedens*) fishery was started in the 1970s, and only male crabs are allowed to be landed. As a result, there are discards of females and undersize males. Currently, no regulations limit the minimum legal size for red crabs, although fishermen have been using selective fishing gears and practices to capture mostly male crabs with a carapace width of larger than 105 mm. Under the Exempted Fishing Permit (EFP) given in 2010, very limited female landings were allowed, and as a result female landings were recorded only in 2010 and 2011. The conical traps used include an escape vent to allow for the release of smaller crabs, the traps are set in a specific depth range that maximizes the catch (600 - 900 m), and the traps are fished for one day to maximize catch rate and minimize trap saturation before the bait is consumed. The fishermen sort the catch on the deck of the fishing vessels discarding females that they are prohibited from landing and smaller, unmarketable males. The performance of the traps used in this fishery is not well understood, nor is the amount and fate of discarded red crabs from fishing operations. The performance of the traps includes the size selectivity of the gear, and the optimum soak time, and this is important to fishermen so that they can maximize the efficiency of their operations. The amount of discarding and the survival of those discards is an important fishery management issue, as dead discards represent a loss to the resource, just as landed red crabs, and these need to be quantified before a credible stock assessment can be pursued.

1.1. Trap size selectivity

In most crab fisheries, the minimum size of the animal retained in the trap is effectively controlled by the escapement ring or vent size. The size of the escape ring or vent is managed so that the animals below the minimum legal size or minimum market size have a high probability of escape from the trap prior to the gear being hauled. This management tool is designed to reduce the capture of undersize animals, hence minimizing the discard mortality due to damage and displacement related to the fishery operation, or post-harvest predation (Treble et al., 1998). Although there is no minimum legal-size limit for red crabs, fishermen have been using selective fishing methods to capture only male crabs with a carapace width (CW) of larger than 114 mm since the beginning of the fishery in the 1970s, and, more recently for crabs larger than 105 mm (Tallack, 2007; Wahle et al., 2008).

Tallack (2007) attempted the first size-selectivity study in this fishery. She utilized a ventless trap as a control gear, and compared the catches of identical traps with escapement-ring sizes of 9, 10 and 11 cm, referred to as small, medium and large, respectively. She conducted the study in water depths of 600 and 800 m in traditional fishing areas off southern New England (Figure 1.1). Tallack (2007), however, did not correctly estimate the selectivity of the experimental gears, as she mis-interpreted the cumulative frequency distribution curves for the catch of traps equipped with the small, medium and large vent sizes as the size selectivity curves. Size-selectivity curves usually evaluate the proportion retained by size. Hence, I have re-analyzed the Tallack (2007) data, to better understand the size selectivity of the traps equipped with the various escape rings. The fishery presently uses a 9-cm escape ring. In subsequent analyses, I will compare the size distribution of the catch of the traps with a 9-cm escape vent, and the size distribution of the landings, and address the question of the possible benefit of increasing the escape ring size to minimize discarding.

1.2. Soak time

The relationship between soak time and catch in stationary gears such as gillnet (Hansen et al., 1998; Kennedy, 1951; Prchalová et al., 2011), hook-and-line (Løkkeborg and Pina, 1997) and trap (Fogarty and Addison, 1997; Jeong et al., 2000) has been well investigated. Soak time directly affects the overall catch of a trap balancing the processes of ingress and egress for the trap, as the catch includes both number and size of crabs at a given time (Miller, 1979; Smith and Jamieson, 1989). Bait effectiveness, accessibility and retention capabilities of a trap change due to soak time (Caddy, 1979). Although accessibility and retention capabilities are a function of trap design and size, crab behavior toward the traps is changed when the trap starts to retain bigger animals. As a result, the size frequency distribution of crabs retained in the trap changes depending on the soak time; the longer the soak time the more large animals retained in the trap (Smith and Jamieson, 1989).

The common approaches to model the saturation of any particular gear often uses deterministic and stochastic models (Fogarty and Addison, 1997). This subject is important to the fishermen, as they usually desire to target a specific size of crab for a specific market, so they inherently use their knowledge of trap performance to modify their fishing operations. Although in this study I do not specifically use these models, I present evidence of the effect of soak time on the catch number and size distribution of the catch.

1.3. *Discard estimation*

The estimation of discards, the weight and number of unwanted species and target species that are below a minimum size, returned to the sea in the process of fishing (Aarts and Poos, 2009; Fernández et al., 2010) and discard mortality are very complicated. The lack of semi-independent surveys and reliable reports from fishermen on the amount of discards have contributed to the uncertainty in estimating size of the red crab population and the intensity of fishing mortality. Although in the red crab fishery the discard of other species is negligible, the discards of females and small males are substantial. Hence, another approach to estimate the rate of discard is essential, so that discard mortality estimation is reliable.

Wahle et al. (2008) attempted to estimate discard mortality and growth rate for deep-sea red crab from tag-and-recapture studies by tagging approximately 10,000 crabs (Wahle et al. 2008). Unfortunately, due to low recovery of recaptured crabs, the result was neither reliable for predicting the discard mortality, nor the growth rate. A study using “stamina index” as a qualitative measure (Benoît et al., 2012) to assess discard mortality in red crab fishery proposed that discard mortality is 5% (Tallack, 2007). The study assigned five levels of a stamina index to the crab after exposure to normal fishing operation and several recapture scenarios. Tallack (2007) reported a discard rate of >71% and a discard mortality of 5%, but her investigation was geographically limited to a small area, and was not representative of the range of the fishery. Additionally, her experiments did not address the potential effects of the geographic displacement of discarded crabs, and the effect that may have on their survival.

In this study, I estimate the spatio-temporal discards (Depestele et al., 2011; Welch et al., 2008) for the red crab fishery for the years 2002, 2010 and 2012 for northern portion of the stock and 2010 and 2012 for southern portion of the stock based on independent sea sampling of the fishery, and a comparison to port-agent sampling of the landings. The red crab stock is spatially divided by Hudson Canyon, and that divide may provide a biogeographic barrier that has resulted in a segregation of this species (Milner, 2012; Rahel, 2007). I utilize the carapace-width frequency distribution from port and sea-sampling data in the given year to estimate the proportion of discards to the landing. I then estimate the proportion of discards in terms of biomass (kg) and number of individuals.

1.4. Discard mortality

The red crab fishery was started in the late 1970s and has been a male-only fishery, with discarded females representing 10-40% of the catch depending on fishing location. The resource has been scientifically sampled using trawl, traps and naturalist dredge (Murray, 1974; Tallack, 2007; Wahle et al., 2008; Weinberg and Keith, 2003; Weinberg and Keith, 2005; Wigley et al., 1975). Wigley et al. (1975) described the spatial characteristics of the red crab resource on the US east coast based on trawl survey data, including the carapace-width (CW) frequency distribution of this resource at that time. Other spatiotemporal studies have been conducted using the same gear (Weinberg and Keith, 2003; Weinberg and Keith, 2005). In this study, I used the spatiotemporal data from previous and current surveys to understand changes in carapace width (CW) of the female population that could be attributed to fishing. Since female red crabs are captured, but not landed, any changes in the female size distribution from the time of the first survey of the resource in the early 1970s to present, may be attributed to discard mortality. The previously mentioned experimental fishery landings of female red crabs in 2010 and 2011 are considered negligible as compared to the male landings, and the estimated stock biomass.

Discard rate and discard mortality have been an issue for the fishery since there are no reliable discard reports and no fisheries observers on board to collect those data. Hence, the stock assessment for this species is far from ideal, since the total amount of removals (landed and discarded) from the fishery is not known. The total removal due to the fishery operations relative to the biomass of the fishable stock is described as fishing mortality. Although the amount of landings is provided in Vessel Trip Reports (VTRs), and dealer reports, the amount of discards from the bycatch has never been summarized and quantified in an accurate way. Hence, it is crucial to estimate both the proportion of discards to landings, and the discard mortality. Unlike many other fisheries that have diverse species bycatch (Alverson, 1994; Garcıa-Caudillo et al., 2000), the discard from this fishery is only undersize males and females (Tallack, 2007).

Tallack (2007) suggested that the discard mortality was ~5% and there were no differences by sex; however, she neglected the displacement of individuals discarded on the relatively steep continental slope. Therefore, the conclusions that could be drawn from the study relative to the fishery-induced discard mortality were limited. In consequence, an investigation into changes in the CW frequency distribution and other statistical properties of the CW distribution with time and within a stock area will give better insight to the mortality caused by fishing (Depestele et al., 2011).

Phenotypic changes due to intensive exploitation (Kuparinen and Merilä, 2007) have been observed in several commercial fisheries (Carver et al., 2005; Dulvy et al., 2004; Reznick and Ghalambor, 2005; Ricker, 1981), resulting in an alteration in size structure and maturity size of the animal (Jennings et al., 1999). Kuparinen and Merilä (2007) suggested that fishing pressure would alter life-history characteristics and produce a genetic shift. The decline of the mean size of the fish in a population, relative to an unfished population, has been long used as a measure of the intensity of fishing pressure on the stock (Beverton and Holt, 1957). A virgin or unfished stock has many larger animals in the population, and as the fishery extends in time, or fishing intensity increases, the larger, older animals are generally removed. As a result, the size-frequency distribution shifts to the left (smaller individuals), and the mean size of the animals in the catch decreases, as the mode of the size distribution also shifts toward smaller crabs.

In this study, I compare the size-frequency distributions of female red crab in the northern area (north and east of Hudson Canyon) from an early pre-fishing survey (Wigley et al., 1975) through a current survey. I have investigated the changes in CW distribution due to fishing activity. I used a multifaceted data set that represents different years, areas and gears used to collect the data. I also compare the observed female CW frequency distribution with a distribution predicted from an age- and size-structured model to demonstrate that the observed CW frequency distribution is similar to those that would be predicted given a very low level of fishing mortality. This implies that discard mortality is low.

2. Methods

2.1. Trap size selectivity

The size-selectivity analysis consisted of two procedures. First, I investigated the effect of vent size, carapace width (CW), sex, and water depth on the number of crabs caught in a ventless trap and experimental traps. The experimental traps used 9-, 10- and 11-cm escapement rings, referred to as small, medium and large vent size, respectively. I employed Poisson's regression and adjusted for over-dispersion to the model. The formula for the model is as follows.

$$log(\mu) = \alpha + \beta_{\ 1} vent\ size + \beta_{\ 2} CW + \beta_{\ 3} Depth + \beta_{\ 4} Sex$$

where μ is the count (number of crabs), α is the intercept and the β's represent coefficients for each of the named variables.

Next, I fitted a logistic model to calculate the probability of retention for every experimental trap relative to the ventless (control) trap. The formula to calculate the probability of retention is as follows:

$$P(y|CW) = \frac{e^{\alpha+\beta*CW}}{1 + e^{\alpha+\beta*CW}}$$

Where α and β are the parameters of the model. The 25-, 50- and 75-percent probabilities of retention for each trap were then calculated using non-linear regression, although these numbers can be calculated algebraically once the parameters are estimated.

Differences in the CW size distribution of the catch as a function of different gears were studied using the Kolmogorov-Smirnov test (K-S). The test was conducted based on the empirical cumulative distribution function of CW given different gear. The K-S test was implemented using PROC NPAR1WAY in SAS 9.2.

The K-S test statistic function is given by:

$$D = \max_{x}(F_{Control}(x) - F_{Experimental}(x))$$

2.2. Effect of soak time on trap catch and size distribution

To analyze the effect of soak time on catch number and size distribution, I separated the overall Northwest Atlantic red crab-fishing zone into north and south areas. As a result, I have attempted to minimize bias if there are differences in size-frequency distributions among the populations sampled (Smith and Jamieson, 1989). Since I do not have soak times as time-series data, I only investigated the mean catches and catch size distribution as functions of soak time for the north and south areas. I used analysis of variance if no assumptions for that parametric test were violated; otherwise, I used Kruskal–Wallis's non-parametric test to compare the median. The comparison of mean, median and size distribution is necessary because the effect of soak times to the CW of the red crab aught varied during the data collection.

To analyze sex ratio from the catch, I used a chi-square test to investigate the proportion of male and female crabs at any given soak time. I also used the chi-square test to investigate if there is an association between sex, soak time and area. For average catch-per-trap analysis, since I did not count the number of crabs for every trap I sampled, a test to evaluate changes of male or female crabs given the different soak time would not be reliable due to small sample sizes. I calculated average-catch-per-trap from every trawl/string instead of from every trap. For example, in the 2012 survey of northern portion, only three trawls (21 traps) were sampled from five days soaking time and 18 trawls (163 traps) from one-day soaking time. Hence, there are three observations for each sex for five-day soak time compared to 18 observations for one-day soak time.

2.3. Discard estimation for the red crab fishery

For the discards analysis I separated the available information based on the year and area (north and south). To ensure that I compared the samples from the same area, I only used the port sample data from the statistical area where I conducted the sea sampling. The sea samplings were conducted in the area where regular fishing occurs, hence both samples are good spatial representations of fishing operations for the commercial fishery in the respective areas.

Given the fact that sea sampling always provides larger sample sizes than port sampling, comparing them in straightforward logistic regression for discard proportion would not be appropriate. Hence, I compared the relative distribution from both samples in 5-mm bin sizes to estimate discard proportion in the given length class. For male discards, I assumed that there would be no landed crabs below the minimum landing size in a given year from port samples and no high grading of discards (Depestele et al., 2011; Gillis et al., 1995), whereas all females were assumed to be discarded. This method is adapted from the fisheries selectivity conducted by Wahle (2008). I defined the discard rate at given bin size (Δd) for males as

$$\Delta d_l = \frac{Rf_{ss} - Rf_{ps}}{Rf_{ss} + Rf_{ps}}$$

Where Rf_{ss} and Rf_{ps} are relative frequencies from sea and port sampling, respectively. I then fitted this value (Δd_l) with a logistic regression as:

$$P(y|\Delta d_l) = \frac{e^{\alpha+\beta*\Delta d_l}}{1 + e^{\alpha+\beta*\Delta d_l}}$$

Where *y* is the probability of crab will be discarded.

For the total discard, I incorporated the prediction of female to male ratio. I assumed that at the fishing ground, there would be lower proportion of large females to males (Tallack, 2007; Wahle et al., 2008; Weinberg and Keith, 2003; Weinberg and Keith, 2005). To obtain a good representation of the amount of discards, I converted number at carapace width (CW) into weight at width based on CW-weight relationship using separate male and female values for the relationships (Wahle et al., 2008).

2.4. Discard mortality

In this study, I utilized two types of data, secondary and primary data. I obtained the secondary data from the principal investigator of another project or digitized directly from a project report. Those data consist of observations from trawl surveys (1974, 2004-2005) and trap surveys (2002, 2010). I collected the primary data over two year periods (2012 and 2013) through semi-independent trap surveys on board of FVs Benthic Mariner, Diamond Girl and Hannah Boden.

The primary data collection served two purposes, as a tag recovery effort for 2010 tagging project (Wahle, pers.comm.) and biological data collection. Unfortunately, I did not recover a single tagged crab in those three trips (more than 10,000 crabs sampled). As for biological sampling, I recorded the carapace width

(CW), sex and egg color for all red crabs observed. Because this data collection was a semi-independent survey, modification of the sampling method was necessary. I planned to sample 10% of the total traps in every trawl; this plan, however, did not work since I had to sample one trap at a time to minimize the heat exposure to the crabs. Hence, the sampling frequency of traps was dependent on the time required to measure all the crabs from the previous trap and weather or logistic conditions that may or may not directly influence my observations.

The secondary and primary data were collected from different gears. Hence, I conducted exploratory data analysis to investigate whether or not the distributions could be analyzed using parametric statistics. I used parametric tests (ANOVA and t-test) if appropriate, and conducted non-parametric tests (Wilcoxon-Mann-Whitney (W-M-W) and Kruskal-Wallis (K-W)) when assumptions for parametric test were violated. The W-M-W test has higher power than the t-test when the underlying populations have asymmetric distribution and it was used whenever a t-test was not appropriate. The K-W test is a generalization of the two-sample Wilcoxon-Mann-Whitney test to three or more groups. In addition, I compared the slopes of the descending sides of the CW frequency distribution using an Analysis of Covariance (ANCOVA) to investigate changes in the effects of fishing-related mortality on the female CW frequency distribution in the northern area. I also used an age-structured model (Fournier et al., 1998) to simulate the carapace width frequency distribution of red crabs under different fishing mortality levels for females in the northern portion of the stock. I chose this area since there is a good spatial overlap in the data collection and the northern area is suspected to experience higher fishing activity than the southern portion of the stock. I used previous studies to set other parameters such as maximum carapace width (Haefner, 1977), natural mortality (Serchuk, 1977) and the current study for the parameters of gear selectivity.

3. Results

3.1. Selectivity study.

The field survey for the selectivity study was conducted in a small area of the upper continental slope, east of Hudson Canyon in the northwest Atlantic (Figure 1.1). Although there are differences in catch per unit effort (CPUE) and number of female and male red crab between the 600 and 800 m depths, depth and sex did not affect the number of crabs captured in control and experimental gears (Table 1.1). These parameters were significant only when crabs larger than 105 mm were modeled (Table 1.2). Hence, for selectivity analysis, I consider only carapace width (CW) and escapement ring sizes in the calculations.

The number of crabs captured in the control trap was always higher than that in other experimental traps, specifically in small, medium and large vent size, respectively (Figure 1.2). According to the selectivity curve (Figure 1.3), the larger the escapement vent, the larger the $CW_{50.}$ The catch characteristics showed significant differences across the treatments (control and various experimental gears) in terms of their means and medians (Table 1.3). The mean carapace width, however, is not a good measure when the normality assumption does not hold. Hence, in this study the median was used as the appropriate term to compare the central value from the distribution. Comparison of the crab CW distribution caught in the control gear to each experimental gear using Kolmogorov-Smirnov test indicated that the CW distribution in each experimental trap is significantly different from that in the control trap, as well as in the other experimental gears ($p \leq 0.001$) (Table 1.4). The CW_{50}

values for the 9-, 10-, and 11-cm escape vents were estimated to be 90, 99, and 107 mm, respectively.

3.2. Effect of soak time on catch and size distribution.

In the 2012 field data from north and south area (Figure 1.4), the mean catch per unit effort (CPUE) decreased significantly when the soak time increased (Figure 1.5), although in some observations the mean was not appropriate to test the difference due to the violated assumption of parametric test. The median CPUE indicated that the catch from a 1-day soak was substantially different from that from a 5-day soak (Table 1.6). In the 2013 field data, neither the mean nor the median could be statistically compared due to insufficient number of observations, although I found that mean CPUE decreased as the soak time increased (Figure 1.5). I observed the same general trend of catch per trap when female and male catch data were separated (Figure 1.6), even for crabs equal to or larger than 90 mm CW (Figure 1.7). In both the southern and northern portions of the stock, the proportion of males was always higher than the proportion of females, regardless of the soak time, for crabs larger than or equal to 90 mm (x^2 <0.001) (Table 1.8).

In the northern area, the CW distribution for female red crab differed significantly with soak time (Table 1.7). In the southern area, however, neither the 2012 and 2013 survey data indicated a significant difference in CW distribution with soak time. In the northern area, the increase in soak time produced a reduced size distribution (lower SD) and shifted the curve slightly to the right side of the distribution. This indicates the trap retained larger crabs as smaller crabs were released through the escape vents as soaking time is increased (Figure 1.8). In the southern area, for 2012 field data, the mean and median were not significantly different as well. For female crabs in the 2013 field data, soak time did not result in a change in the size distribution, although the standard deviation was greater for the 5-day soak (Figure 1.9).

3.3. Discard estimation in red crab fishery

The CW frequency distributions from port and sea sampling are presented in Figure 1.9 and 1.10 for northern and southern portions of the stock, respectively. The vertical grey line in Figure 1.10 and 1.11 is included to orient the reader to gear selectivity used in the surveys, and to emphasize that the discard proportion is a function of fishermen on-deck sorting selectivity rather than the gear selectivity on the seabed. Observed and predicted discard selectivity of male red crabs for both portions of the stock are presented in Figure 1.12.

The proportion of total discards to landings of males in the northern portion of the stock area has decreased from 1.35 to 0.27 from 2002 to 2012, a 53% decrease from 2002 to 2010 and 58% decrease from 2010 to 2012, in terms of observed discard biomass (kg). Using 2002 as the reference, there was also an 80% decrease in the discards to landings proportion from 2002 to 2012, in terms of weight and number of discarded crabs. In general, the discard proportion for males to total landings has also been decreasing from 0.47 in 2002 to 0.27 in 2012. As a result in 2012, the discards were predominantly female red crabs. By 2012, the female discards were ~75% of total discards in weight, and ~70% in number of all discarded crabs, while in 2002, female discards of red crabs were only ~50% in weight and ~55% in the number of the total catch.

The decreasing pattern of total discards to landings of males was also observed in the southern portion of the stock, as the proportion of total discards to landings decreased from about 0.80 in 2010 to 0.10 in 2012, an 85-90% decrease in the proportion of discards to landings, in terms of biomass and number of crabs respectively. Female discards were also dominant in both 2010 and 2012, and represented about 50% and 80% of total discards by weight, respectively. Proportion of male discards to total discards in the southern portion of the stock was relatively low compared to the northern area. It decreased by 57% in terms of biomass and 45% in terms of the number of crabs from 2010 to 2012.

3.4. Discard mortality

In order to simplify the analysis, the results were grouped based on the area where the surveys were conducted (Figure 1.13). Hence, years, gears and sex were the variables in the observations. I analyzed the carapace width of female crabs in the northern area and the outputs are in the form of descriptive statistics (Tables 1.14), statistical inferences (Table 1.15) and CW frequency distribution plots (Figure 1.14). Parametric and non-parametric statistics combined with basic descriptive analysis were employed to gain more insight into red crab population dynamics.

The female CW frequency distributions from 1974 through 2012 demonstrated a remarkable similarity given the differences in sampling gear and time (Figure 1.14). Females are not harvested; therefore, any changes in the size-frequency distribution either are due to changes in the stock structure, the gear selectivity, or discard mortality. There was no significant difference in the median of the female crabs caught from trawl surveys (Table 1.15). For female size distribution caught by traps in 2002, 2010, and 2012, there also appears to be no temporal trend in the right side of the distribution, although a test on the median and mean indicated that they are significantly different from each other (Table 1.15). The mean size varied between 90 and 99 mm and median ranges from 93-100 mm over the 40-year sampling period from both trap and trawl survey. It is surprising that the size distributions with the largest crabs were observed in the most-recent survey (Figure 1.14). I also found that there are no significant differences in descending slopes of CW distribution for trawl and trap survey (Figure 1.15 and Table 1.16). This slope is a function of natural and fishing mortality in the age-structure model. I used an age structured model with assumed values for K (0.15), M (0.2) and L_{inf} (120 mm) to estimate a predicted CW frequency distribution at F=0 and F=0.05. Comparison of observed and predicted CW frequency distributions indicates good agreement, especially between the observed CW distributions and the predicted CW distribution with F=0.05. Therefore, I conclude that the discard mortality of females is about 5%.

4. Discussion

4.1. Size selectivity study

The median of CW distribution in each gear was mistakenly identified as the CW_{50} selectivity parameter in the Tallack (2007) study (Figure 1.2). The selectivity should refer to the proportion of animals captured in control and experimental gears (Rudershausen et al., 2008; Shepherd et al., 2002; Treble et al., 1998), and the CW_{50} is the carapace width at which the probability of retention reaches 50% or 0.50. Hence to reanalyze this study, I used the control trap to identify the size distribution of crabs present in the area. This enabled me to conduct selectivity analysis for each experimental gear (vent size). However, the control traps (no escape vents) were overcrowded with smaller size crabs, and did not collect more of the larger size crabs, and this is problematic for selectivity analysis (Figure 1.2). This caused the proportion of each experimental trap to control trap to exceed one (Figure 1.3-left). As a result, I had to adjust the analysis for the lower and upper tail of the size distribution in our selectivity analysis. Hence, for selectivity analysis, I did not use the observations that exhibited a descending pattern in the left side of the distribution and a proportion that exceeded one in the right side of the distribution. This observation suggests that smaller crabs will swarm the trap first, and they will leave the trap once larger animals enter the trap. Agonistic behavior increases at the time of feeding (Clark et al., 1999; Jachowski, 1974), and this corresponds with the time the crab contacts the gear, and the larger and more aggressive crabs prevent the smaller crabs from enter the trapping and force the smaller crabs to escape the trap (Miller, 1978). Hence, the larger animals will dominate the trap, and this affects the selectivity. In this study, the control and experimental traps were located in areas with a standing stock of small and large animals (corresponding to a healthy stock). The smaller number of larger size crabs caught in control traps did not automatically mean that there were few crabs; it rather means that once a trap is overcrowded, small and large animal avoided the traps (trap saturation). The intimidation from animals inside traps in terms of odor produced from ammonium (Zimmer-Faust et al., 1984), sound and threatening posture triggered this avoidance (Miller, 1990).

The CW_{50} (CW that corresponds to 50% probability of retention) shows high correlation with the size of escapement ring (Table 1.3). The selection curves for each experimental gear show a relatively steep slope (Figure 1.2) suggesting the effectiveness of the gear excluding small crabs. The selectivity curves show that larger vent size resulted in larger animals, but reduced the number of desirable size crabs (Table 1.3). Thus, the use of larger escape vents clearly results in the retention of larger red crabs, but given the small number of larger crabs in the catch, this result does not imply that the use of larger escape vents makes good economic sense. I confirm the conclusions from the previous study that the 9-cm escapement ring, currently used in the fishery, will optimize the catch of desirable size crabs (Tallack, 2007). This conclusion was drawn based on the number of desirable crab (> 105 mm) retained in the experimental gears. I also found contradictory results that crab mean size in the catch did not agree with the trap selectivity size (CW_{50}) for each experimental trap. I found that there was a decreasing pattern of crab mean size in the catch given the larger escapement ring (Table 1.3). One would expect that the increase of escapement ring would increase the mean size of crabs caught by the trap. Tallack

(2007) acknowledged that the data collection departed from normal commercial operation, where the fishermen target the areas with larger size crabs. The observations from the shallow location (600 m) indicate mostly females with a smaller mean size (Table 1.5). The current fishing strategy is reasonable since most of the bait is still intact and can sustain another 24-hour soak time. In addition, there is no limitation on how many traps can be employed, which favors this strategy as well.

4.2. Effect of soak time on catch and size distribution.

Catch per unit effort (CPUE) in a trap fishery is often defined as the number of crabs captured divided by the number of traps deployed during the fishing operation. Therefore, in a trap fishery, count or catch per trap can be used as an index of abundance to estimate population size (Bennett and Brown, 1979; Slade and Blair, 2000), although this measure is sometimes questioned due to the effect of soak time on the number of crabs captured and size distribution (Caddy, 1979). This index is useful and can be improved by including the soaking time as the denominator in the analysis (Goñi et al., 2001). Hence, if the average soaking time is 24 hours, the CPUE will be crabs per trap per 24 hours.

A decrease in catch per trap in relation to soak time for the whole catch (Figure 1.5), compared to that for crabs equal to or larger than 90 mm (Figure 1.7) was identical. The catch per-trap decreased as the days of soak time increased. The decrease of catch per-trap for male red crabs was greater for female, as indicated by the steeper slope, although the male proportion from the catch was always significantly greater than female. The fishing operation is effective in targeting male crab as well as larger crabs, as the change in catch per trap was very small even when the crabs larger or equal to 90 mm were omitted from the calculation (Figures. 1.6 and 1.7).

For male crabs, the change in soak time significantly affected the mean and the median size of the crabs regardless of the location and year of the survey. In 2012 field data, the effect of soak time in the northern area was the same as with female red crabs. Soak time narrowed the standard deviation and shifted the distribution to the right, while in the southern area only the left side of the distribution was shifted to the right. The soak time effect was clearly observed in the southern area for the 2013 survey. I observed an obvious shift of the whole distribution to the right, and the standard deviation was wider, indicating that traps were retaining medium-sized crabs and even larger crabs after a five day soak. In this analysis, I assumed the crabs' behavior in the two areas toward the trap is the same; hence, population size probably plays an important role on these occurrences. To further understand the effect of soak time, I suggest that more complete studies of this topic be conducted in the future so the red crab fishermen are able to maximize their fishing efficiency.

4.3. Discard estimation in red crab fishery

In this study, I did not consider high-grading as an important factor to be included in discard analysis. Size selection by traps used in the red crab fishery resulted in a specific size range of captured crabs. On-deck sorting of the trap catch is a second selection process, which is done by the fisherman, and results in only desirable or marketable crab size being landed. The male discard probability is a function of the fishermen sorting process, and this is a function of market conditions. The only reason for discarding a male crab of marketable size is the carapace condition; crabs with soft shells are discarded. It is apparent that the decrease in the male discard proportion in the northern and southern portions is a result of the fisherman being more selective in the post catch, deck sorting operation,

I found that the discard probability curve has become steeper or more knife edged, which means the vessel crews are discarding the more undesirable crabs (< 90 mm) and retaining more crabs larger than 90 mm (Figure 1.12) due to fishermen discarding smaller crabs captured in the traps. Sea sampling of the trap catch indicates an increase in the mean size of the crabs in the catch, and NMFS data indicate a recent increase in mean size of crabs landed.

The proportion of female discards to total discard from the fishery has increased over time, and the mean size has decreased in both areas over the years, although only the southern area was significant. This raises the question of cause and effect related to this finding. Even though this fishery is considered a mature fishery, fishermen sometimes will explore a new “fishing ground." It does not necessarily mean that they are fishing in the different area; it rather implies that they will fish in deeper or shallower water than the standard fishing operation. This practice sometimes leads to the capture of more female red crabs. Hence, I suggest conducting a study to investigate this relationship and to include large females in the landings. Unlike males, I suggest that there should be a minimum harvest size for female red crab.

My observations suggest that discarding is heavily affected by a market demand. Therefore, if a new market develops for larger, live crabs, I expect that there will be a change in fishing behavior that affects the discards as well. Hence, to investigate this hypothesis, sea sampling followed by port sampling should be conducted in the same trip.

4.4. Discard mortality

Investigating the health of a deep-sea red crab stock by looking at the size distribution in multiple year data sets can be problematic. Red crabs are segregated by depth (Hastie, 1995; Lindberg and Lockhart, 1993), and their susceptibility to different gears as a function of size may affect the observed size-frequency distributions in the data. It also appears that the red crab stock in the US has two distinct populations, north (east) and south of Hudson Canyon. An assumption of an equal annual recruitment is fundamental to this analysis. I also assumed that a healthy stock has high resilience to fishing pressure so that there will be delayed response to low fishing pressure, and it will recover soon after the disturbance passes or weakens (Brunel and Piet, 2013).

In the northern area, the lack of changes in CW frequency distribution indicates a minimum effect of fishing mortality to the female red crab. The lack of a difference in the descending slope on the right side of the distribution from two types of surveys has also strengthened this conclusion. In addition, my model shows a reasonable similarity to the observed data given two different scenarios of fishing mortality, suggesting an annualized discard mortality of females of about 5%, similar to the results of the Tallack (2007) study (Figure 1.14). Hence, I conclude that fishing is not significantly affecting the female population in the northern area. Recalling that the fishing operations occur in specific depths with more males than females, this area offers limited flexibility for the fishermen to set the traps because of the short distance between fishing borders. On average, the distance from the depth of 400 to 800 m is only 1to 2 km. Therefore, I am particularly confident of the results and conclusions drawn from this area since the spatial effects play a minimum role.

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Table 1.1. Analysis of Maximum Likelihood Parameter Estimates for number of captured crabs. Zero values indicate the reference class.

Parameter		Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept		3.8031	0.2192	3.3735	4.2326	301.14	<.0001
Gear	Control	0.0000	0.0000	0.0000	0.0000	.	.
	Small	-0.2786	0.0894	-0.4537	-0.1034	9.71	0.0018
	Medium	-0.5593	0.0999	-0.7550	-0.3635	31.37	<.0001
	Large	-0.8541	0.1101	-1.0700	-0.6383	60.13	<.0001
Width		-0.0103	0.0022	-0.0147	-0.0060	21.58	<.0001
Sex	Female	0.0000	0.0000	0.0000	0.0000	.	.
	Male	0.0352	0.0771	-0.1158	0.1863	0.21	0.6477
Depth	Shallow	0.0000	0.0000	0.0000	0.0000	.	.
	Deep	-0.1462	0.0761	-0.2954	0.0030	3.69	0.0548

Table 1.2. Analysis of maximum likelihood parameter estimates for number of captured crab larger than 105 mm. Zero values indicate the reference class.

Parameter		Estimate	Standard Error	Wald 95% Confidence Limits		Wald Chi-Square	Pr > ChiSq
Intercept		13.4310	0.7895	11.8836	14.9784	289.41	<.0001
Gear	Control	0.0000	0.0000	0.0000	0.0000	.	.
	Small	0.7021	0.1067	0.4931	0.9111	43.33	<.0001
	Medium	0.2164	0.1189	-0.0167	0.4494	3.31	0.0688
	Large	-0.3954	0.1404	-0.6706	-0.1202	7.93	0.0049
Width		-0.1026	0.0072	-0.1166	-0.0885	204.75	<.0001
Sex	Female	0.0000	0.0000	0.0000	0.0000	.	.
	Male	-0.1977	0.0826	-0.3596	-0.0357	5.72	0.0168
Depth	Shallow	0.0000	0.0000	0.0000	0.0000	.	.
	Deep	-0.4411	0.0880	-0.6136	-0.2686	25.12	<.0001

Table 1.3. Carapace width characteristic and selectivity of experimental gears. Caret (^) indicates inappropriate test due to violations of assumption. P is the result from parametric test and Np is the result from non-parametric test. CW is in mm.

Summary	Vent size				
	Control (ventless)	Small (9 cm)	Medium (10 cm)	Large (11 cm)	P-value
Mean	92	97	95	94	P: <.0001^
SD	9	11	12	12	-
Median	92	98	94	93	Np: <.0001
CW at 25% prob.	-	78	87	96	-
CW at 50% prob.	-	90	99	107	-
CW at 75% prob.	-	101	110	119	-
Mean Count (>=105)	5	9	6	3	Np: <.0001

Table 1.4. P-value of multiple comparison of carapace width distribution of crabs caught from control and experimental gear using Kolmogorov-Smirnov test.

Gear types	Control	Small	Medium	Large
Control	-	<.0001	<.0001	0.0001
Small	<.0001	-	<.0001	<.0001
Medium	<.0001	<.0001	-	0.0012
Large	0.0001	<.0001	0.0012	-

Table 1.5. Number of crabs caught in each gear from both locations, 600 m (shallow) and 800 m (deeper).

Gear	Location	Female	Male
Control	Shallow	882	736
	Deeper	24	1239
Small	Shallow	931	561
	Deeper	33	808
Medium	Shallow	613	440
	Deeper	14	545
Large	Shallow	444	336
	Deeper	16	407
Sub.Total	Shallow	2870	2073
	Deeper	87	2999
Grand Total		2957	5072

Table 1. 6. Number of catch per trap in each survey. Tilde (˜) indicates that the test is appropriate. $\bar{x}$= mean. Mean was compared using ANOVA and median was compared using Kruskal-Wallis test.

Soak time (day)	North -2012				South -2012				South -2013			
	$\bar{x}$	SD	Med.	Var.	$\bar{x}$	SD	Med.	Var.	$\bar{x}$	SD	Med.	Var.
1 day	70	30	60	895	53	8	53	63	22	11	16	115
4 day	-	-	-	-	-	-	-	-	13	1	13	1
5 day	28	11	21	124	36	9	36	79	8	1	8	2
P-value	0.0279		0.0085˜		0.0117˜		0.0244˜		0.1852		0.0371	

Table 1. 7. Comparison of carapace widths collected after the indicated periods of trap deployment. Tilde (˜) indicates that the test is appropriate. $\bar{x}$ = mean. The p-values indicate the test for mean and median.

Female

Soak time	North -2012				South -2012				South -2013			
	$\bar{x}$	SD	Med.	Var.	$\bar{x}$	SD	Med.	Var.	$\bar{x}$	SD	Med.	Var.
1 day	96	10	98	91	101	9	101	80	112	9	111	81
4 day	-	-	-	-	-	-	-	-	112	8	111	66
5 day	103	8	104	70	102	8	103	63	116	11	114	127
P-value	<0.0001		<0.0001˜		0.1464˜		0.113˜		0.0617˜		0.2566˜	
K-S test 1-5 day	p-value < 0.0001				p-value = 0.2429				p-value = 0.3215			

Male

Soak time	North -2012				South -2012				South -2013			
	$\bar{x}$	SD	Med.	Var.	$\bar{x}$	SD	Med.	Var.	$\bar{x}$	SD	Med.	Var.
1 day	100	9	101	74	106	10	107	110	116	11	115	124
4 day	-	-	-	-	-	-	-	-	123	11	121	118
5 day	103	8	105	65	108	9	108	73	128	13	127	158
P-value	<0.0001		<0.0001˜		<0.0001		<0.0001˜		<0.0001		<0.0001˜	
K-S test 1-5 day	p-value < 0.0001				p-value < 0.0001				p-value < 0.0001			

Table 1. 8. Number of Catch and average number of catch per trap of crabs greater than or equal 90 mm. F = Female, M = male.

	North-2012			South-2012			South-2013		
Average catch/trap Catch	F	M	Pr > ChiSq	F	M	Pr > ChiSq	F	M	Pr > ChiSq
1_Day	11	48	-	2	47	-	3	19	-
	732	3501	<.0001	134	2631	<.0001	188	1031	<.0001
4_Day	-	-	-	-	-	-	3	9	-
	-	-	-	-	-	-	95	308	<.0001
5_Day	7	19	-	6	29	-	1	7	-
	130	389	<.0001	140	743	<.0001	26	261	<.0001

Table 1. 9. Observed and predicted landings and discards for northern portion of the stock in 2002.

North 2002	Weight (kg)		Unit (# crabs)	
	Observed	Predicted	Observed	Predicted
Total Captured (M & F)	1114	1120	4907	5004
Males landed	473	473	1690	1690
Males discarded	302	302	1481	1481
Females discarded	339	345	1736	1833
Total discarded	641	647	3217	3314
Prop. discard to landing	1.353	1.366	1.904	1.961
Prop. male discard to total discard	0.471	0.467	0.460	0.447
Prop. female discard to total discard	0.529	0.533	0.540	0.553
Prop. of male to female discard	0.890	0.875	0.853	0.808

Table 1. 10. Observed and predicted landings and discards for northern portion of the stock in 2010.

North 2010	Weight (kg)		Unit (# crabs)	
	Observed	Predicted	Observed	Predicted
Total Captured (M & F)	802	704	3387	3042
Males landed	486	486	1872	1872
Males discarded	168	168	863	863
Females discarded	148	50	652	307
Total discarded	316	217	1515	1170
Prop. discard to landing	0.649	0.447	0.809	0.625
Prop. male discard to total discard	0.531	0.771	0.570	0.738
Prop. female discard to total discard	0.469	0.229	0.430	0.262
Prop. of male to female discard	1.131	3.360	1.324	2.816

Table 1. 11. Observed and predicted landings and discards for northern portion of the stock in 2012.

North 2012	Weight (kg)		Unit (# crabs)	
	Observed	Predicted	Observed	Predicted
Total Captured (M & F)	1591	1583	5568	5550
Males landed	1253	1253	3932	3932
Males discarded	87	87	514	514
Females discarded	251	243	1122	1104
Total discarded	338	330	1636	1618
Prop. discard to landing	0.270	0.263	0.416	0.412
Prop. male discard to total discard	0.258	0.264	0.314	0.318
Prop. female discard to total discard	0.742	0.736	0.686	0.682
Prop. of male to female discard	0.348	0.359	0.458	0.466

Table 1. 12. Observed and predicted landings and discards for the southern portion of the stock in 2010.

South 2010	Weight (kg)		Unit (# crabs)	
	Observed	Predicted	Observed	Predicted
Total Captured (M & F)	1701	1476	6450	5791
Males landed	933	933	3051	3051
Males discarded	318	318	1598	1598
Females discarded	450	225	1801	1142
Total discarded	768	543	3399	2740
Prop. Discard to landing	0.823	0.582	1.114	0.898
Prop. male discard to total discard	0.414	0.585	0.470	0.583
Prop. female discard to total discard	0.586	0.415	0.530	0.417
Prop. of male to female discard	0.707	1.411	0.888	1.400

Table 1. 13. Observed and predicted landings and discards for the southern portion of the stock in 2012.

South 2012	Weight (kg)		Unit (# crabs)	
	Observed	Predicted	Observed	Predicted
Total Captured (M & F)	2373	2330	5792	5678
Males landed	2158	2158	4971	4971
Males discarded	38	38	214	214
Females discarded	178	134	607	493
Total discarded	215	172	821	706
Prop. Discard to landing	0.100	0.080	0.165	0.142
Prop. male discard to total discard	0.176	0.220	0.260	0.302
Prop. female discard to total discard	0.824	0.780	0.740	0.698
Prop. of male to female discard	0.213	0.282	0.352	0.434

Table 1. 14. Descriptive statistics for the female red crab in northern area.

Year	Survey	Number	CW Mean	SD	Median	Var.	Mode	Range	IQR
2002	Pot	1739	93	9	95	80	98	71	12
2010	Pot	652	99	10	100	98	100	56	14
2012	Pot	1122	97	10	99	92	101	56.5	14
1974	Trawl	535	90	16	93	266	95	103	16
2004-05	Trawl	2247	90	16	94	267	70:100	96	22

Table 1. 15. Results of parametric (significant at the 0.05 level are indicated by *) and non-parametric tests (indicated by the p-value) for female in the northern area.

i/j	Trap 2002	Trap 2010	Trap 2012	Trawl 1974	Trawl 2004_05
Trap 2002		<.0001*	<.0001*	1.0000	1.0000
Trap 2010	<.0001*		0.0255*	<.0001	<.0001
Trap 2012	<.0001*	0.0255*		<.0001	<.0001
Trawl 1974	1.0000	<.0001	<.0001		1.0000
Trawl 2004_05	1.0000	<.0001	<.0001	1.0000	

Table 1. 16. Comparison of the slopes from two surveys using an Analysis of Covariance.

Trawl

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
CW	1	0.05938	0.05938	154.802	<.00001
Year	1	0.00094	0.00094	2.455	0.145
CW : year	1	0.00011	0.00011	0.283	0.605

Trap

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
CW	1	0.12431	0.12431	57.762	<.00001
Year	1	0.00736	0.00736	3.422	0.0856
CW : year	1	0.00064	0.00064	0.297	0.5942

Figure 1. 1. Survey location**.**

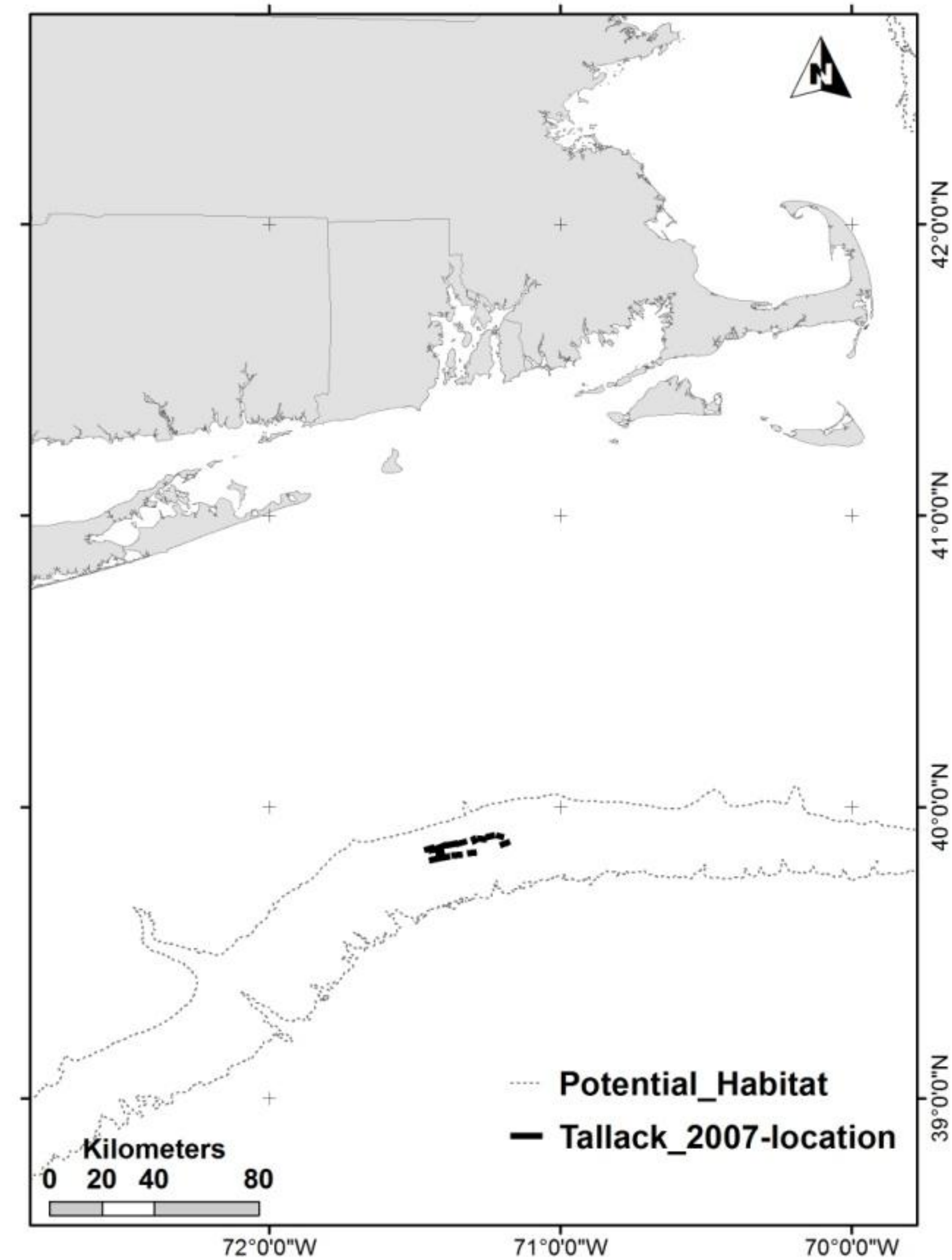


Figure 1. 2. Carapace width distribution of the catch (left) and its cumulative distribution function (right).

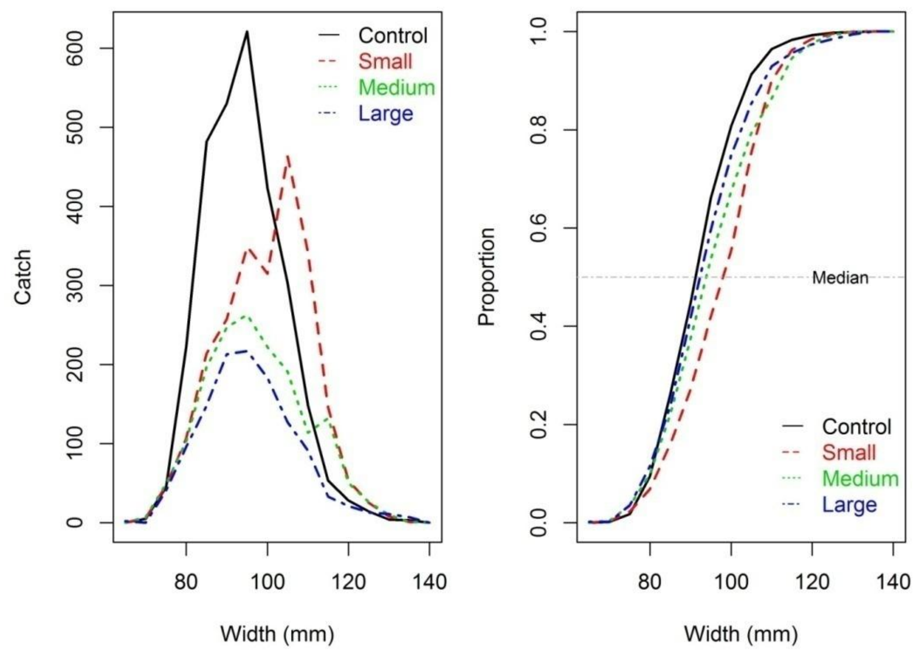


Figure 1. 3. Catch proportion of experimental gear to the control trap (left), and selectivity curve for three different vent sizes (right).

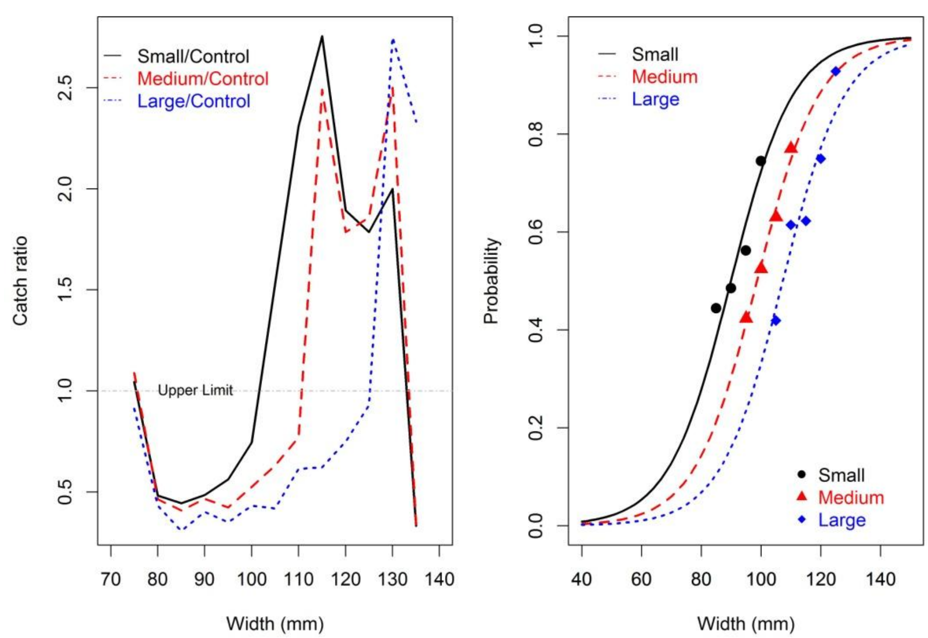


Figure 1. 4. Map of the 2012 and 2013 survey locations.

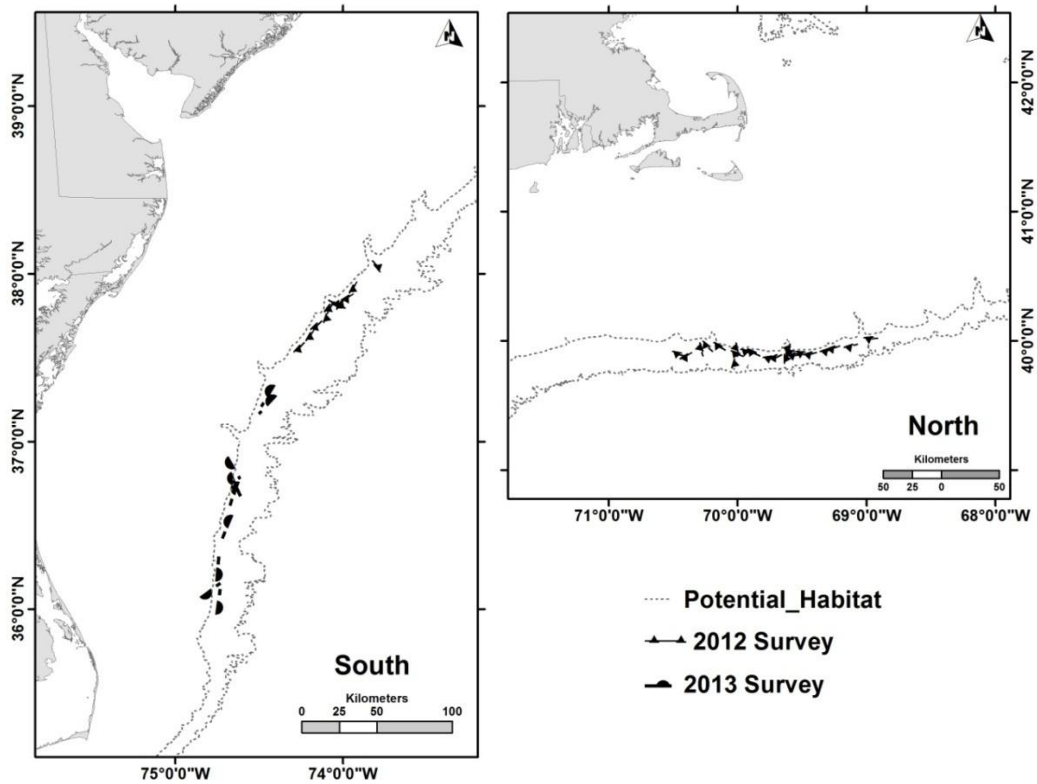


Figure 1. 5. Number of pooled male and female catch per trap and soak time in 2012 and 2013 survey.

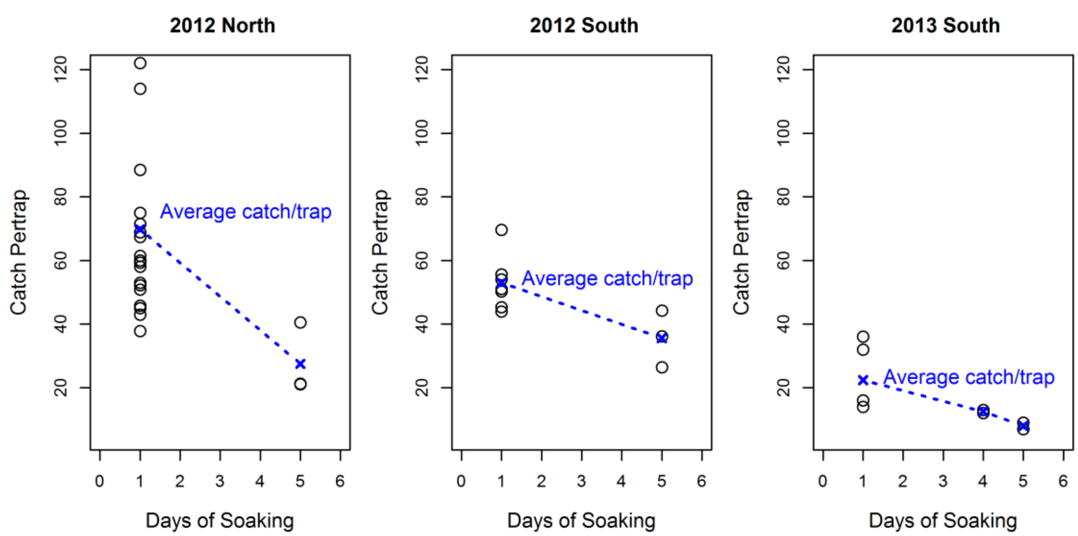


Figure 1. 6. Number of male and female catch per trap and soak time in 2012 and 2013 survey.

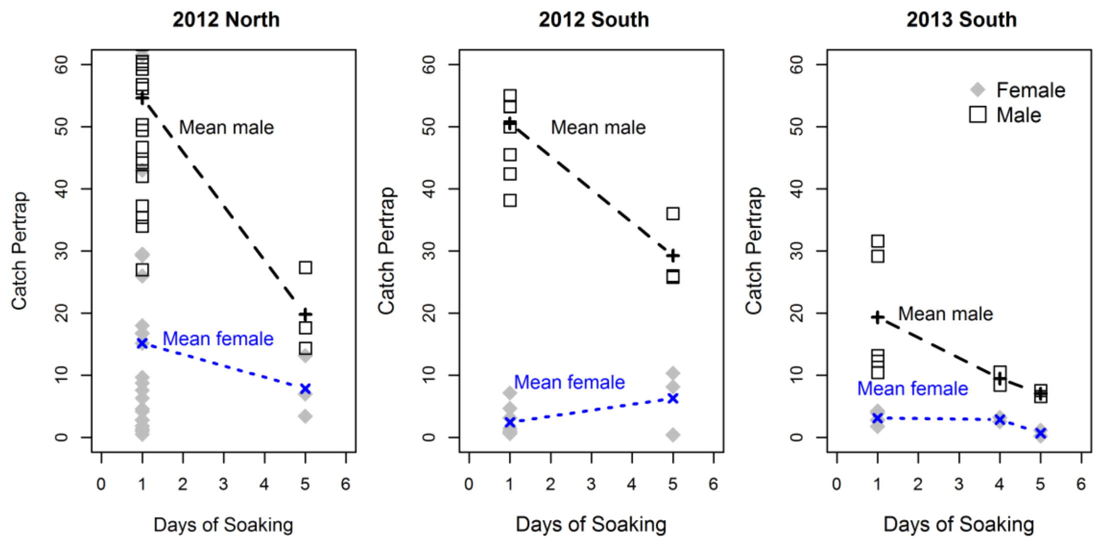


Figure 1. 7. Number of male and female catch per trap and soak time in 2012 and 2013 survey for crab greater than or equal to 90 mm.

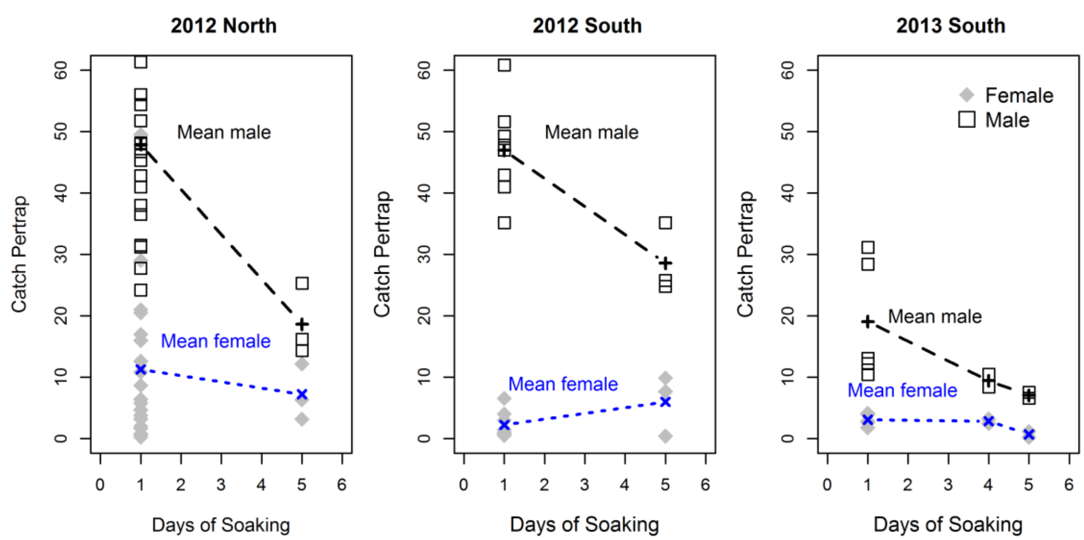


Figure 1. 8. Carapace width frequency distribution of 2012 survey.

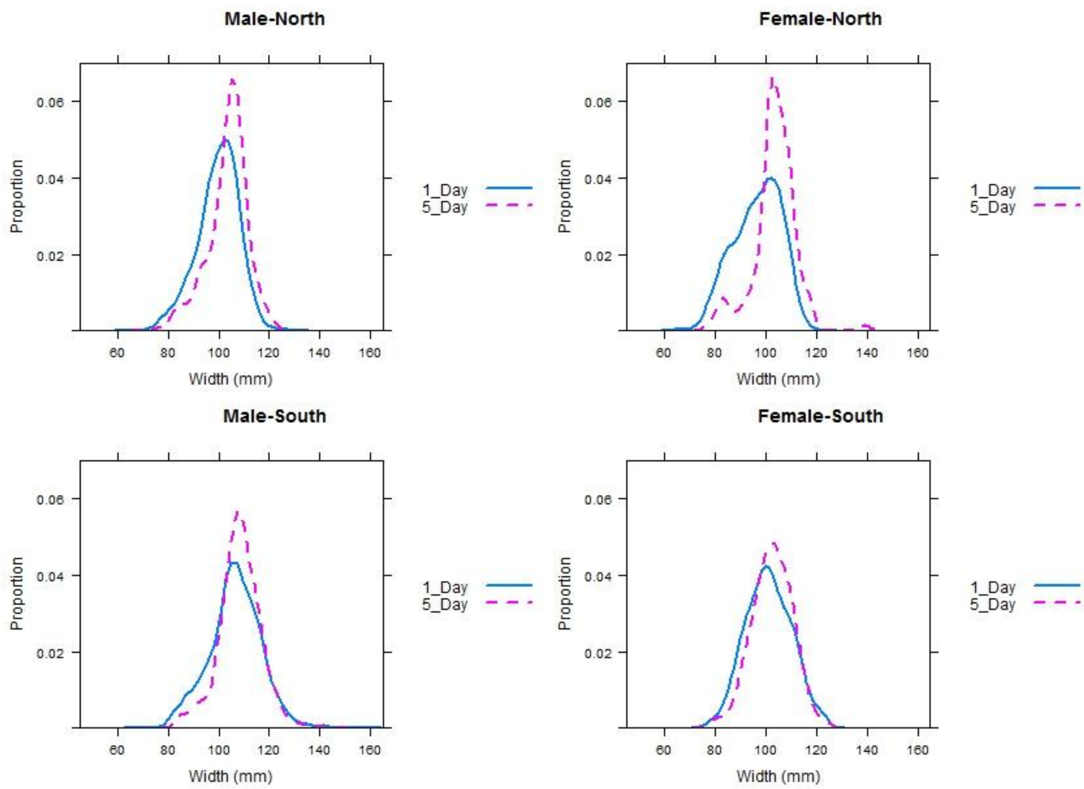


Figure 1. 9. Carapace width frequency distribution in 2013 survey for southern stock only.

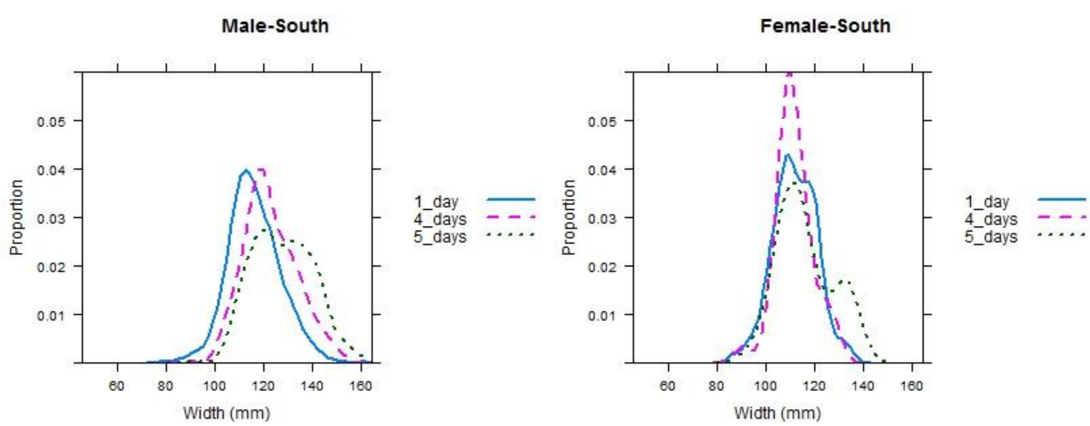


Figure 1. 10. Carapace width frequency distribution from port (male only) and sea sampling (male and female) for the northern portion of the stock. Grey line represents the CW_{50} for the gear used in the survey.

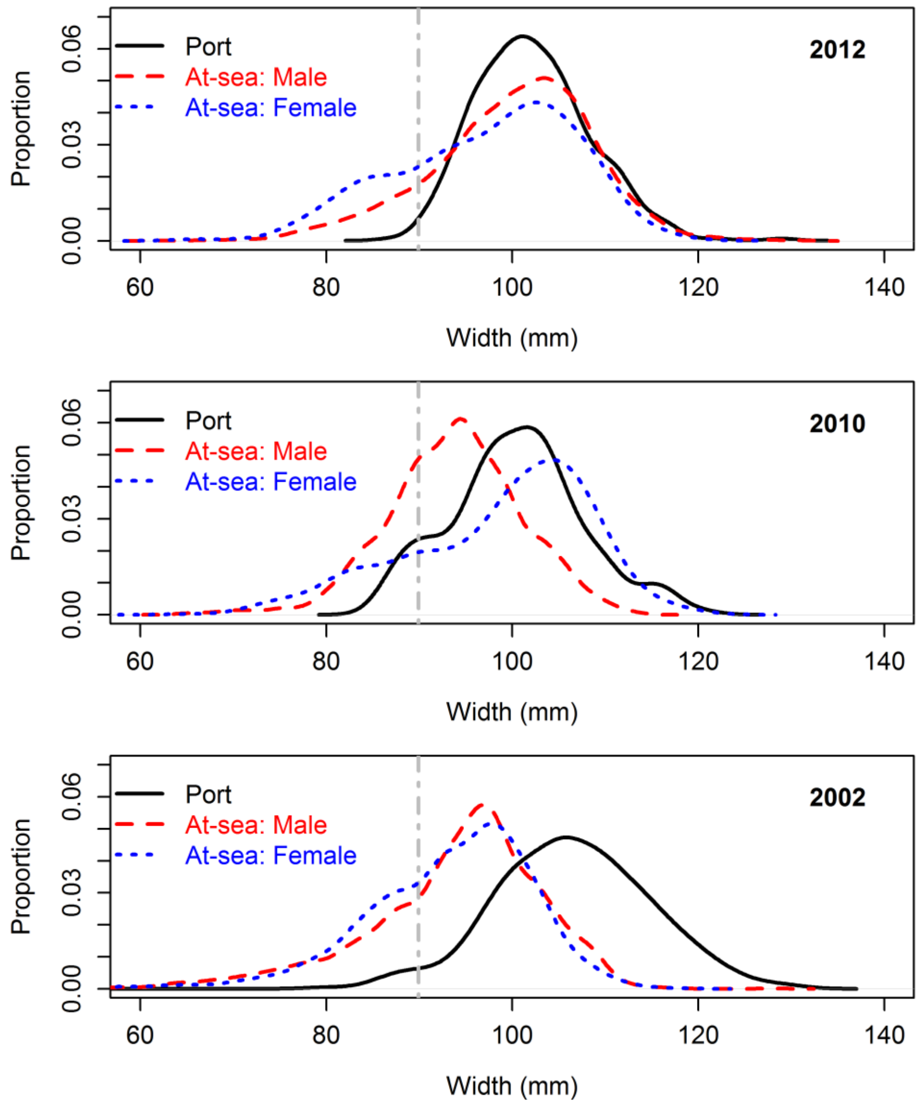


Figure 1. 11. Length-frequency distribution from port (male only) and sea sampling (male and female) in southern stock. Grey line represents the CW_{50} for the gear used in both survey.

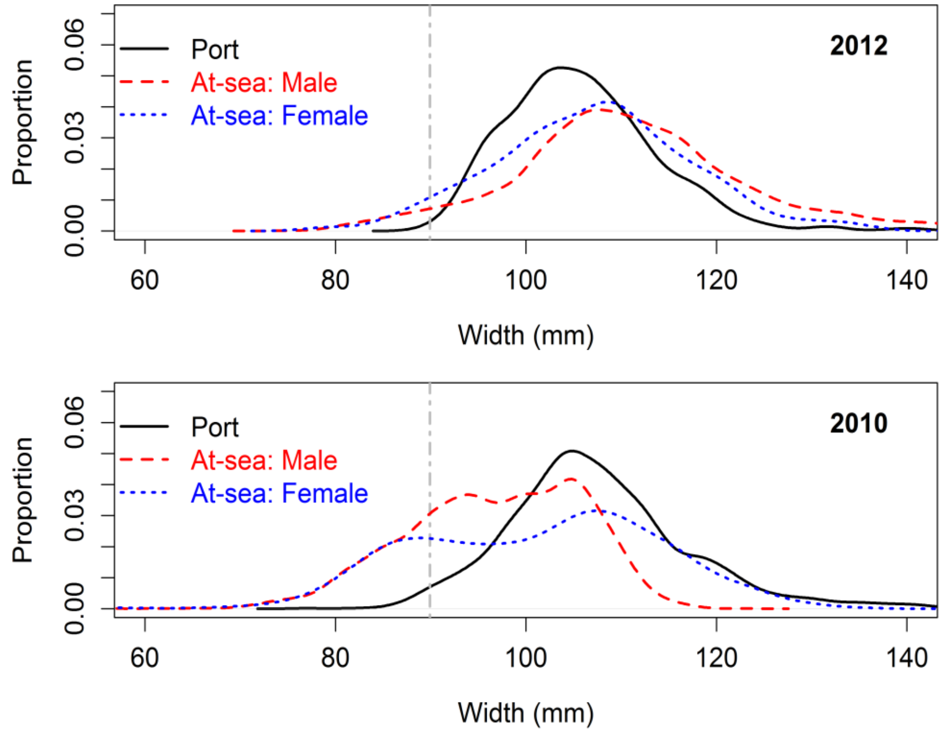


Figure 1. 12. Discard probability for areas north and south of Hudson canyon. Lines represent predicted values and symbols represent observed values.

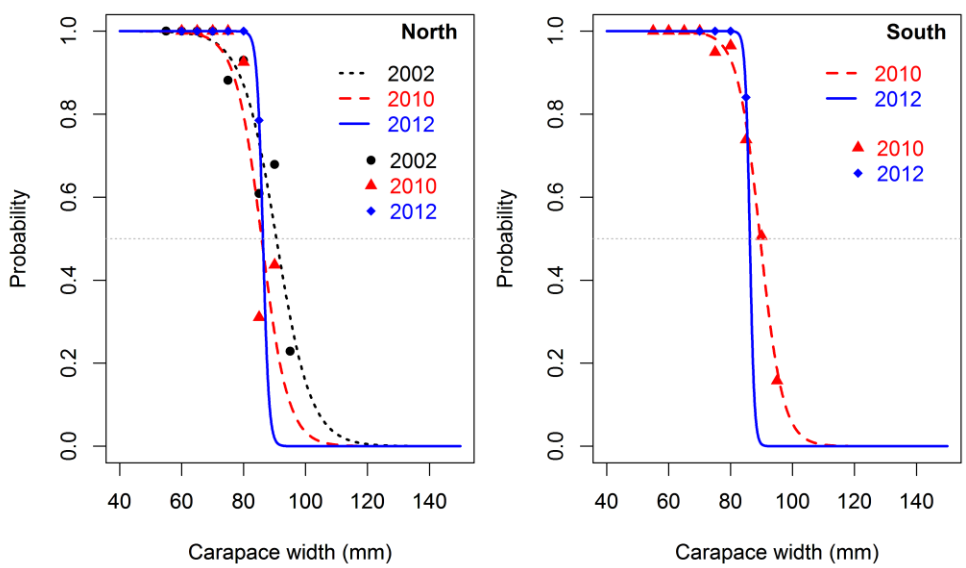


Figure 1. 13. Map of the northern area for all surveys.

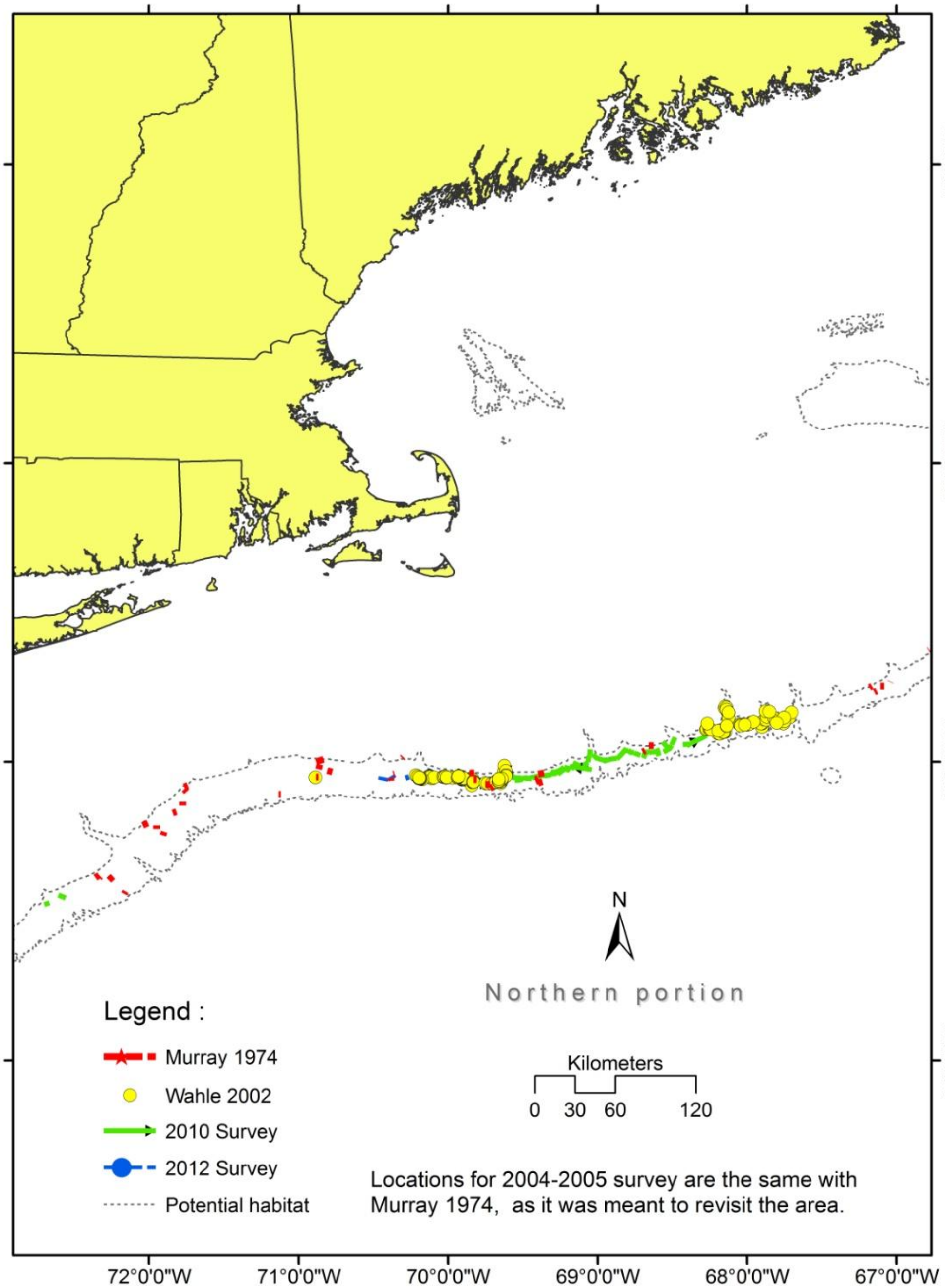


Figure 1. 14. Carapace width (in mm) frequency distributions for female red crabs in the northern portion of the study area.

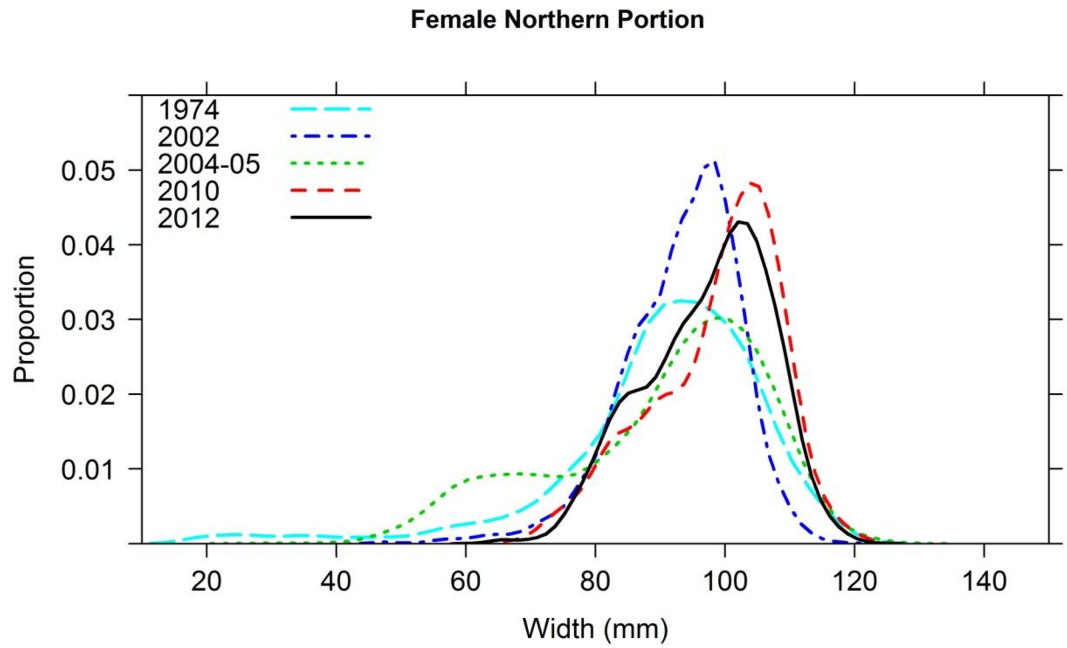


Figure 1. 15. Comparison of descending slope of the female CW frequency distribution from trawl and trap surveys.

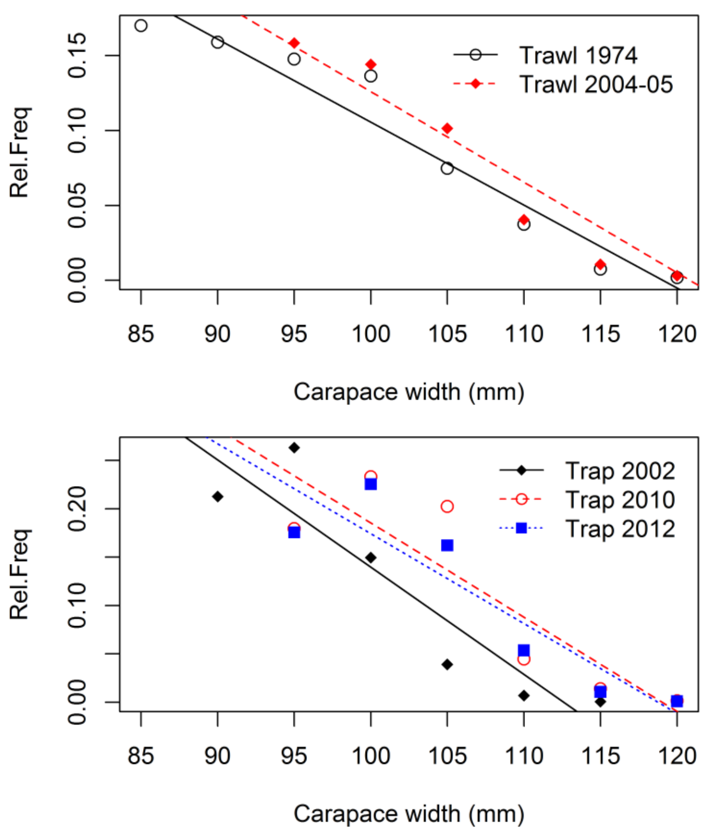
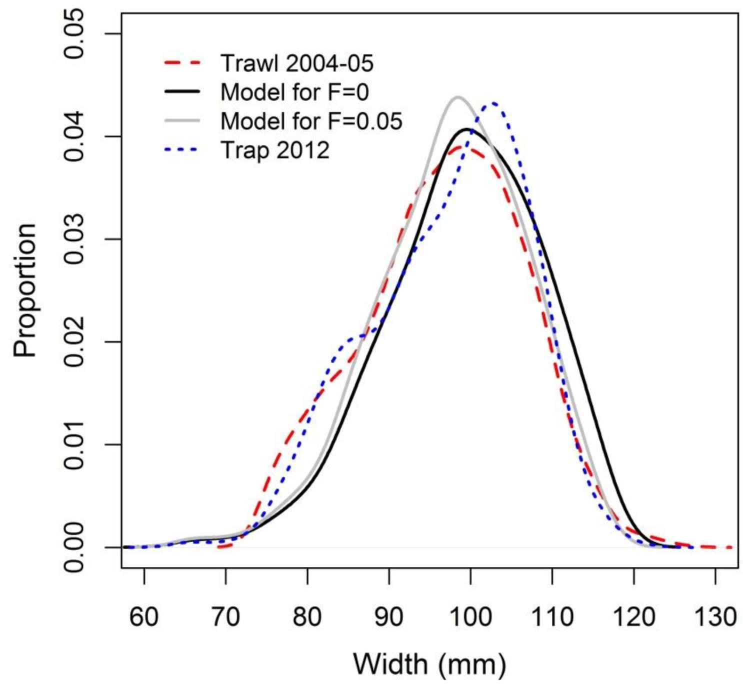


Figure 1. 16. Comparison of observed and predicted female CW frequency distribution for red crab in the northern area.



Manuscript-2

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Effects of harvesting on size distribution of the red crab population in the Northwest Atlantic: implications for female mating success and the estimation of fishing mortality on males

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Effects of harvesting on size distribution of the red crab population in the Northwest Atlantic: implications for female mating success, and the estimation of fishing mortality on males

ABSTRACT

The Northwest Atlantic red-crab (*Chaceon quinquedens*) fishery was started in the 1970s and has been based on the harvest of male crabs only. Management of the fishery relies on fishery independent surveys conducted in 1974 and a 2003-2005. The fishery has changed the red crab population in terms of the ratio of females to males, and the mean size of mature females and males. In this study, I have investigated the changes in the carapace width (CW) size distribution due to the fishing activity, and estimated the probability of female mating success and male fishing mortality.

In the area where the fishing occurs, I found that the proportion of females to males for the largest size class (CW>115 mm) indicates a higher number of males. Although there has been concern regarding mating success for females due to lack of large males, I found no evidence to support this hypothesis. I found that the probability of successful mating in the logistic model increases with a carapace width. I also observed that comparison of mating success from the 1974 to the 2004-05 surveys for the southern area indicates a higher probability of mating success in the more recent years.

The result of catch-curve analysis indicates evidence of higher fishing mortality (F) in recent years (2012) for the northern area (F = 0.47) compared to the

southern area (F = 0.20). Although this finding reflects the current fishery status, the estimated F value might be overestimated due to the more selective nature of trap surveys (the catch is aggregated toward the mean carapace width) and these values are valid only for the localized areas (600-800 meters) where the fishing operations occur.

1. Introduction

1.1. Evaluation of changes in carapace width distribution of males

The Northwest Atlantic red crab (*Chaceon quinquedens*) fishery was started in the 1970s and has been based on the harvest of males only. The resource has been scientifically sampled using trawl, traps and naturalist dredge (Murray, 1974; Tallack, 2007; Wahle et al., 2008; Weinberg and Keith, 2003; Weinberg and Keith, 2005; Wigley et al., 1975). Wigley et al. (1975) described the spatial characteristics of the red crab resource on the US east coast based on trawl-survey data, and the initial (prior to fishing) condition of carapace width (CW) frequency distribution of this resource. Other spatiotemporal studies have been conducted using similar gears (Weinberg and Keith, 2003; Weinberg and Keith, 2005).

1.2. Implications for female mating success

Fishery independent surveys of the red crab stock on the continental shelf of North America have been attempted twice, in 1974 (Wigley, 1975) and 2003-2005 (Wahle et al., 2008; Weinberg and Keith, 2003). In the more recent assessment, there was evidence of an increase in the male biomass by 75%; however, large males (> 114 mm) decreased by 43% compared to 1974 survey (Northeast Data Poor Stocks Working Group, 2009). In addition, there was a 20% increase in biomass of fishable male red crabs in the recent survey and a 250% increase in the biomass of large, female red crabs (90+mm). It was postulated that this increase could be due to size-selective fishing (Weinberg and Keith, 2003), or high recruitment in the years prior to the recent survey (Northeast Data Poor Stocks Working Group, 2009).

Based on the assessment in 1974 and the 2003-2005 survey, the male-only fishery has changed the red crab population in terms of the ratio of females to males, and the mean size of mature females and males (Northeast Data Poor Stocks Working Group, 2009). Between 1974 and 2003-2005, the ratio of all females to males increased by 133%, while mean size of mature males (75+ mm) decreased by 7% and that of females (70+ mm) increased by 1%. Additionally, the decrease of large, male red crabs with size of 114+ mm by 43% has raised a concern about the mating success that eventually could lead to recruitment failure for the stock. Therefore, a thoughtful assessment of changes in sex ratio of larger, mature crabs as indicated by changes in the length-frequency distribution between males and females will substantially add to the current management discussions to either optimally fish the stock by harvesting females to balance the population numbers, or remain with current male-only harvest to preserve the female spawning stock.

To successfully reproduce, males must be larger than the females (NFSC, 2006), as males must embrace smaller females (Jivoff, 2003) during copulation that lasts 12-13 days for *C. quinquedens* (Elner et al., 1987). In unfished populations, the size distribution of males and females ensures that males are larger than females (Haefner, 1977). However, in fished populations, especially in a male-only fishery, the size distribution of males will be altered or truncated as larger males are harvested first, unless there is a compensation response of the population to harvesting. Therefore, there is the potential issue of a limitation on mating success due to an inadequate number of large males. Sex ratio can also become an important issue in mating success since red crabs are partially segregated based on depth (Hastie, 1995;

Lindberg and Lockhart, 1993). Females dominate in more shallow depths, and males dominate in deeper depths (Hastie, 1995). Hastie (1995) suggested that there is an upslope migration for male and downslope for female in order to mate.

Spawning activity occurs in any geographic region that the crabs inhabit (Haefner, 1978; Lux et al., 1982; Wigley, 1975); hence, pheromones play an important role as species-specific attractants in red crab reproduction (Krång and Ekerholm, 2006). Male mating success is even more complicated than female since it will also be influenced by the competition among males. Haefner (1977) found mating evidence in female red crabs by the presence of a scarred/abraded vulva. Therefore, in a mating success study, this observation can also be treated as evidence of successful mating and the data can be treated as binomial distribution with a scarred vulva treated as success and no eggs or scarring as an indication of no mating activity.

In my study, I used the spatiotemporal data from previous and current surveys to document and understand changes in CW of the male population that can be attributed to fishing. I first examined the changes in the proportion of males to females for trawl and trap catch data for the last 40 years. I investigated the catch characteristics of trawl and trap catch data from multiple years for the entire population as reflected in the catch and based on four CW categories. This analysis provides information on how the size of the crabs may affect mating success. Finally, I investigated mating success based on an analysis of the probability of observing egg-bearing female and females with vulva scarring to the probability of observing large females without eggs and scarring (Elner et al., 1987; Haefner, 1978). The models utilize the combination of both types of evidence (optimistic model) and egg-bearing-only evidence (conservative model) as a success in the binomial distribution (i.e. a value of 1, rather than a value of 0).

1.3. Estimation of fishing mortality on males

NMFS data indicate that landings have been reasonably stable at approximately 2000 mt since 2002, when the red crab Fishery Management Plan (FMP) was implemented (NFSC, 2006). At that time, fishing mortality for maximum sustainable yield (F_{msy}) was determined to be unknown due to lack of information on growth, recruitment, and natural mortality (M). Hence, implementation of a length-based catch population assessment model was also determined to be inappropriate at the time (NFSC, 2006). These issues have lead to uncertainty in defining the US Northwest Atlantic red crab stock characteristics.

Phenotypic changes due to intensive exploitation (Kuparinen and Merilä, 2007) have been observed in several commercial fisheries (Carver et al., 2005; Dulvy et al., 2004; Reznick and Ghalambor, 2005; Ricker, 1981), resulting in alteration in the size structure and size at maturity of the animals (Jennings et al., 1999). Kuparinen and Merilä (2007) suggested that fishing pressure could alter life-history characteristics and produce a genetic shift. The decline of the mean size of the fish in a population, relative to an unfished population, has been long used as a measure of the intensity of fishing pressure on the stock (Beverton and Holt, 1957).

A virgin or unfished stock has many larger animals in the population, and as the fishery extends in time, or fishing intensity increases, the larger, older animals are generally removed. As a result, size frequency distribution shifts to the left, and the mean size of the animals in the catch decreases, as the mode of the size distribution shifts to the left. For deep-sea red crab, changes in CW distribution can be used to assess the stock condition due to fishing pressure. A linear regression of a logarithmic transformation of observed length frequency distribution (Pauly, 1983; Sickle, 1977) into specific age structure (Quinn and Deriso, 1999), is a well-known and accepted methodology to assess fishing mortality specifically when age-based data are not available (Smith and Addison, 2003). It assumes that there is equal annual recruitment of both sexes to the population and no variability in recruitment among years. Although this is reasonable for deep-sea red crabs as there is little seasonal or inter-annual environmental variability in its habitat along the upper continental slope (Milliman and Wright, 1987; Wigley et al., 1975), nothing is known about impact of the pelagic larval stage on recruitment.

An investigation into changes in the CW frequency distribution and other statistical properties of the CW distribution with time and within a stock area will provide insight on the mortality caused by fishing (Depestele et al., 2011). In this study, I compared the male size frequency distributions from an early pre-fishing survey (Wigley et al., 1975) through post-fishing surveys to the current survey. I investigated the changes in CW distribution due to fishing activity. I used a multifaceted data set that represents different years, areas and gears used to collect the data. I also used the observed CW frequency distribution of the unfished male population from1974 in areas north and south of Hudson canyon to estimate the life history characteristics of the population. In addition, I used recent observations of the CW frequency distribution of the fished population to estimate fishing mortality of male red crab using a length-based catch-curve analysis (LCCA), substituting CW for length.

2. Methods

2.1. Evaluation of changes in the male carapace width distributions

In this study, I utilized two types of data; primary and secondary data. I collected the primary data over two years, 2012 and 2013, through three semi-independent trap surveys on board three red crab fishery vessels. Secondary data were obtained from the principal investigator of another project or digitized directly from the project report (Murray, 1974; Northeast Data Poor Stocks Working Group, 2009). They consist of observations from trawl surveys (1974, 2004-2005) and trap surveys (2002, 2010, 2012 and 2013).

The primary data served two purposes, as a tag-recovery effort (from Wahle's tagging program) and biological data collection. Unfortunately, we did not recover a single tag in those three trips. Because this data collection was semi-independent, modification of the planned sampling method was necessary once at sea. I planned to sample 10% of total traps in every trawl, but this plan did not work since I had to sample one trap at a time to minimize the heat exposure to the crabs. Hence, the sampling was dependent on the time required to measure all the crabs from the previous trap and weather or logistic conditions that may or may not directly influence my observations.

The secondary and primary data were collected from different gears. Hence, I conducted exploratory data analysis to investigate whether or not the distributions could be analyzed using parametric statistics. I used parametric test (ANOVA and t-test) when appropriate and non-parametric test (Wilcoxon-Mann-Whitney and Kruskal-Wallis or K-W tests) when assumptions for parametric tests (normality and equality of variance) were violated. The Wilcoxon-Mann-Whitney test has higher power than the t-test when the underlying populations have an asymmetric distribution. The K-W test is a generalization of the two-sample Wilcoxon-Mann-Whitney test to three or more groups. The comparison of mean, median and size distribution is necessary because the effect of gear type to the CW of the red crab caught varied during the data collection.

2.2. Implications for female mating success

To understand the red crab spatial distribution, I first evaluated the catch characteristics of two different gear types (traps and trawls) that have been used to sample the red crab population (Figure 2.4). The trawl survey collected red crab from various depths (shallow and deep) and the trap survey collected samples from a more narrow depth range where the commercial fishing occurs, to maximize the catch of the commercially valuable males. First, I calculated the ratio of mature males to mature females. Then, I compared the sex ratio (female and male proportion) of the total catch using a Chi-square test to determine whether the ratio of female to male is significantly different from 1.0 for the whole catch and for four CW categories. The four size categories are based on observed selectivity in the fishery and are:

CW classes	Fisheries selectivity
< 90	Discarded
90 - 105	Likely discarded
105 - 115	Likely retained
> 115	Retained

In this analysis, I used trap survey data from 2002, 2006, 2010, 2012 and 2013 survey (Table 2.5), and I used data from 1974 and 2004-2005 for trawl survey. I also used the 2006 data to investigate differences in the CW distribution as well as sex composition in depths of 600 and 800 m (shallow and deep locations). Additionally, I evaluated the change in mating success probability that could be related to a fishery effect for the southern area, comparing my 2013 model results with the same model being fit to Haefner's (1977) data as the data were collected from approximately the same areas.

Observations of female red crabs can also include qualitative measures such as the color of the eggs and the presence of scarring since in some cases the females have mated but not extruded the eggs (Turner et al., 2003). An orange color indicates an early development of the egg and dark as late development of the egg. Regardless the color of eggs, I treated this observation as the same variable (an indication of mating success). I used only data from 2012 and 2013 to avoid a mistake since this is a qualitative measure where there is a possibility of difference in defining the parameters. I converted this qualitative data into the form of a binomial distribution and analyzed it by means of logistic regression. To seek an appropriate model to analyze the mating success of female red crab, I explored the possibility of different logistic regression models. At first, I compared an additive logistic regression model to the model with an interaction between the carapace width and the survey area. In the second method, I considered two ways of defining the mating success. The "conservative" model was developed based on the presence of eggs only, while the "optimistic" model was developed based on the presence of either eggs or vulva scarring as an indication of success (Haefner, 1977; Knuckey, 1996). In addition, in order to evaluate the effect of the fishery on mating, I compared the conservative model for 2013 observation to the Haefner (1977) observations in the southern area as both sets of data were collected in the same areas.

2.3. Estimation of fishing mortality on males.

I used the observations in 1974 as a reference in estimating the total mortality (Z) and I used this estimate as the natural mortality (M) of the stock. To estimate the total and fishing mortality in a given year, I used the field observations that I made in 2012, 2013 and previous observations from 1974, 2004-05 (Murray, 1974; Northeast Data Poor Stocks Working Group, 2009) and 2010 (Wahle, tagging project). I assumed that there was no significant fishing effect to influence this deep-sea red crab population in 1974 (Gerrior, 1981; Steimle et al., 2001; Weinberg and Keith, 2003; Wigley et al., 1975). Hence, the total mortality after this year is a function of natural mortality and fishing mortality (F). I also assumed that the natural mortality is constant in every year. In this analysis, I also divided the red crab population into two areas (north and south of Hudson Canyon) as in the previous analyses in this study.

To assign the age to the observed carapace width (CW) to all the data, at first, I constructed an age-length key (Isermann and Knight, 2005) utilizing an age structure model to fit the length frequency distribution from the 1974 data. During the process, I explored the use of different combinations of growth rate (K) and maximum size (CW∞) while keeping the natural M at 0.2 (Serchuk, 1977). Considering the result from the previous section of this study on CW distribution, I used different values for maximum CW in the model and kept the same value for growth rate (K=0.1) for both areas. The K value is reasonable since the red crab is a slow-growth animal. A series of calculations were conducted to generate length (substituting CW_t for L_t) at age (L_t), and numbers of individuals remaining in the population at the given year due to natural mortality only (N_t) and with additional fishing mortality (NF_t). I also incorporated the probability of fish at the given length to be captured by the fishing gear (P_{sel}). The equations are:

$$L_t = L_\infty(1 - e^{(-kt)})$$

where k is the instantaneous growth rate and t is age of the animal. The unfished population is estimated by

$$N_t = N_{(t-1)} \times e^{-M}$$

and the gear selectivity by

$$P_{sel} = (1 + e^{(-\alpha_1 * (L_t - \beta_1))})$$

where α_1 is steepness of the curve and β_1 is the length at 50% probability of being captured. Number in the population affected by two types of mortality (F and M) is calculated as:

$$NF_t = NF_{(t-1)} \times e^{-((P_{sel} * F) + M)}$$

Hence, the predicted catch (N_c) at the given length/age is calculated as:

$$Nc_t = (NF_t - N_{Ft-1}) * \left[\frac{P_{sel} * F}{(P_{sel} * F) + \mathrm{M}}\right]$$

The results from this series of calculations were then compared to the 1974 data to see if the CW distribution of the model is identical with F=0 and M=~0.2.

Finally, I employed a catch curve analysis (CCA) to estimate the total mortality. This procedure was conducted using regression of the linearized form of the following equation.

$$N_t = N_0 \times e^{-Zt}$$

As Z = F+M the fishing mortality after 1974 was simply calculated by subtracting the absolute value of the slope (total mortality, Z) from the natural mortality estimate in 1974. I employed the fisheries stock assessment package (FSA, version 0.4.6) in the process of assigning an age-length key to the observation in each year as well as CCA (Ogle, 2014). Further, I divided the fishing mortality by the total mortality to calculate the exploitation rate (E=F/Z) (Ricker, 1975).

3. Results

3.1. Evaluation of changes in the male carapace width distributions.

In order to simplify the presentation, the results are grouped based on the area where the surveys were conducted (Figure 2.1). Hence, years of observation, gears and sex are the variables. I analyzed 11,864 males in the northern area and 10,307 in the southern area. The outputs are in the form of descriptive statistics (Tables 2.1 and 2.2), statistical inferences (Table 2.3 and 2.4) and CW frequency distribution plots (Figure 2.2 to 2.3). Parametric and non-parametric statistics combined with basic descriptive analysis were employed to gain more insight into red crab population dynamics.

The male crabs in the northern area exhibited variation in both the mean and median CW over the year as the result of harvesting (Figure 2.2). The changes were significantly different for the trawl survey and the trap survey except for the 2002 to 2010 comparison. The frequency distributions in 1974 and 2004-2005 have very different size frequency distributions, with the 1974 distribution indicating many large crabs and the 2004-2005 distribution indicating many small crabs. The 1974 size distribution included many year classes with 29% of the sampled crabs greater than 120 mm CW, and a mode of 116 mm, while the mode of the 2004-2005 distribution was about 70 mm, although there was a weaker mode of 115 mm. In contrast, the trap-captured size distributions all indicate few small or large crabs, with modes ranging from 94 to 101 mm. With respect to the trap survey, the mean size in 2012 data was significantly larger than in 2010. This finding is also confirmed with Kolmogorov-Smirnov test that shows significant difference (p-value <.0001) in the CW distributions between years.

The male frequency distribution in the southern area showed the same pattern as the northern area (Figure 2.3). There was a significant decrease in the median of the distribution from 1974 to 2004-2005 survey. In the 2004-2005 trawl survey data, the size frequency distribution had shifted dramatically to the left, and the mode of the distribution reduced to about 80 mm, although a weaker mode of 116 mm was observed. The mean and median significantly increased from the 2010 to the 2012-2013 survey (Table 2.4). However, the mode from the trap survey only increased slightly from 105 mm in 2010 to 108 mm in 2012-2013.

3.2. Implications for female mating success.

The sex ratios and the catch for each area in a given year provide an interesting comparison when they are analyzed individually based on the gear (Table 2.5 and Figure 2.5 for trap survey, and Table 2.6 and Figure 2.6 for trawl survey). The trap data indicate a significantly higher proportion of males to females, whereas the trawl survey data indicate a higher proportion of females to males (Table 2.5 and 2.6). Interpreting data collected only from one gear will be problematic due to bias toward males for trap and females for trawl. This bias is caused by the fact that trawl surveys were conducted in the shallow water where a higher proportion of females inhabit the area, whereas the trap surveys were conducted in deeper water where males predominate (Figure 2.4). In general, for the trap survey, this finding is consistent for the four CW categories in the northern (Figure 2.7) and southern area except in 2010 (Figure 2.8). The trawl survey also indicated a higher proportion of females in all the classes except the largest class (>115), where the male proportion was higher than that of females (Figure 2.9 and 2.10), although for 2004-05 survey in the southern area, the proportions were not significantly different (Chi-square = 1.08, p-value= 0.2987).

The Akaike Information Criterion (AIC) from the additive logistic regression model and the interaction logistic regression model are 1754.2 and 1756.1, respectively. Hence, the additive model is better since it has lower AIC score (Table 2.7). This exploratory analysis supported separating the analysis based on the fishing area, although I also calculated mating success with both areas combined. For every survey, two models are presented as two different scenarios for evaluating mating success as a function of female carapace width. The conservative model is based on the presence of eggs only, whereas the optimistic model is based on the presence of both eggs and scarring. For the 2012 survey, the coefficients for both conservative and optimistic model are presented in Tables 2.8 and 2.9, respectively. The conservative model indicated a lower slope, consequently, resulting in a lower prediction in the probability of mating success for any given CW compared to the optimistic model. The 2013 survey only covered one area, and its coefficient for both models is presented in Table 2.10. The optimistic model for 2013 observations indicated that most of the female crab showed an indication of success in mating (scar and egg). I also calculated the 95% confidence interval for each model for 2012 (Figure 2.13 and 2.14) and 2013 surveys (Figure 2.15) to give a better perspective of observed data to the model.

3.3. Estimation of fishing mortality on males

The result from the length structure model is an age-length key and it is consistent with the result in the previous section of this study in comparing mean and median size of the captured crabs. The male crabs from the southern area are larger compared to the northern area (Figure 2.17), with an estimated maximum CW for northern area of 145 mm, and southern area of 154 mm. I found fairly similar estimates of natural mortality (M) from both areas in 1974 (Table 2.11 and 2.12), and this result is close to the current estimate of 0.2 (NFSC, 2006). In general, the northern area has a higher fishing mortality than the southern area, except for the 2004-05 observation. However, both areas indicate a similar result because the confidence intervals overlap (Figure 2.18 and 2.19).

The unfished population (1974) in the northern area had an estimated total mortality (= M) of 0.22 and standard error (SE) of 0.02. In 2004-05, I found an estimated total mortality of 0.28 ± 0.02 and an estimated fishing mortality of 0.062. I found higher total mortality in 2010 and 2012, 0.80 ± 0.16 and 0.69 ± 0.04, respectively, compared to 2004-05 observation. It corresponds to a substantial increase in fishing mortality in 2010 and 2012, 0.59 and 0.47, respectively as compared to 2004-05 observation.

The unfished population in the southern area (1974) had an estimated total mortality (= M) of 0.21 ± 0.044. The area also showed an increasing pattern of total mortality in the last 4 decades, though not as high as the northern area. The total mortality was 0.31 ± 0.04 in 2004-05 and 0.42 ± 0.03 in 2012. As for fishing mortality, it was 0.2 in 2012 and 0.11 for 2012-13 observations.

4. Discussion

4.1. Evaluation of changes in male carapace width distributions

Investigating the health of deep-sea red crab stock by looking at the size distribution in multiple year data sets can be problematic. Red crabs are segregated by depth (Hastie, 1995; Lindberg and Lockhart, 1993), and their susceptibility to different gears as a function of size may affect the observed size frequency distributions in the data. It also appears that the red crab stock in the US has two distinct populations, north and south of Hudson Canyon. An assumption of an equal annual recruitment is fundamental to this analysis. I also assumed that a healthy stock has high resilience to fishing pressure so that there will be delayed response to low fishing pressure, and it will recover soon after the disturbance passes or weakens (Brunel and Piet, 2013).

In the northern area, the CW frequency distribution in male is unmistakably a result of fishing pressure. However, I observed a lower slope of the descending limb and a slight shift to the right side of the size frequency distribution as an indication of a recovery process. The sample median from 1974 trawl survey was not significantly different from the 2002 trap survey given the different sampling gear (Table 2.3). In addition, with regard to the larger mean CW in 2012 compared to 2010; this finding is very interesting since the fishery has been targeting only male red crabs. Hence, we would expect that the male size in 2012 should be smaller than in 2010, if fishing intensity is constant and red crab has equal recruitment annually (Table 2.1). Recalling that the fishing operation occurs in specific depths with more males than females, this area offers limited flexibility for the fishermen to set the trap because of the short distance between fishing borders. On average, the distance from the depth of 400 to

800 m is only one to two km. Therefore, I am particularly confident of the results and conclusions drawn from this since the study areas overlap.

The results of the analyses for the southern area are problematic in that not all the samples come from the same area (specific coordinates). In other words, there is not good overlap in the sampling; therefore, it makes it difficult to draw definitive conclusions. There are two possible conclusions that can be drawn regarding the southern area. The first is, if I ignore the spatial effect, then there is an increase in size over the period of the most-recent sampling, and this can be interpreted as an indication of recovery for male red crabs. Presumably, this is related to a decrease in fishing mortality on smaller male crabs allowing the targeted males to grow larger. The conclusion is even stronger when I separate the 2012 and 2013 observations. The other conclusion is that the observed size increase is because the most recent data collected are from slightly to the south of the earlier data. Hence, the distinguished size of crab from northern and southern areas is a result of fishing impact or natural variation size with regard to latitude. If this is the situation, it lends further credence to the argument of two separate stocks, as the southern stock appears to have larger crabs, irrespective of the effects of fishing.

4.2. Implications for female mating success.

To obtain a comprehensive understanding of the red crab spatial distribution, it was very important to analyze red crab sampling data from different gears separately. Analyzing the data from trawl or trap only, would produce a result that might lead to an incorrect conclusion unless one considers the location of the samples. A trawl survey will likely be unable to optimally sample the area where the fishermen are fishing, while the trap survey will be very expensive if it is done independently. Most trap surveys are semi-independent; that is the trap sampling is done to meet the requirements for random sampling, but the sampling locations are also dependent on fishing operations. As sex ratio depends on the depth (Hastie, 1995), the fishermen fish only in areas where the male ratio is higher than female (Tallack, 2007) possibly causing a localized effect of harvesting on the male red crab population. The 2006 data set in Figure 2.11 further explains the differences in the trawl and trap survey data due to the depth difference. Since the crabs were sampled from two different depths, for this reason, it is additional evidence of sex segregation and carapace distribution based on depth.

Because large males are targeted in the fishery and no females are harvested (Wahle et al., 2008), it has been hypothesized that mating success would be a problem for large females (NFSC, 2006; Northeast Data Poor Stocks Working Group, 2009). It was assumed that males should be at least 25 % larger than females (Northeast Data Poor Stocks Working Group, 2009), although in laboratory experiments, males that were 20% larger than females before female molt and 10% larger after the molt were able to complete the copulatory embrace (Elner et al., 1987). Unfortunately, the experiment did not provide many male-female combinations due to stress from handling and different conditions. Elner et al. (1987) also found that females could have multiple matings, even without the molting process. Therefore, the need for a larger male might not be as crucial as it is when molting is required. The evidence of multiple matings in females is also supported from a recent study in which two distinct sperm plugs in female red crabs were observed (pers. Comm. - Bradley Steven-

UMES). In addition, males are also able to do multiple matings with females (Elner et al., 1987). If the percent of increase in female CW is 7-12% after molting (Serchuk and Wigley, 1982), then for the largest female in the fishing area for the 2006 observations, there should have been enough potential males with which to mate (Figure 2.11). The result from the proportion of largest CW classes (>115 mm) from both surveys also indicated a higher proportion of males over females, suggesting that even the largest females have enough males to mate with. Hence, the hypothesis of male shortage for recent years is not appropriate since both surveys indicated a higher proportion of males >115 mm. The result suggests that, if female harvest is necessary to balance the population, this class of very large females should be the first targeted.

In this study, I also investigated the legitimate evidence of mating success such as the presence of eggs and scars in the female red crabs. This approach is not only practical but also provides more certainty in predicting the mating success rather than examining female to male proportions in certain length class since we do not know how big or small male red crabs can successfully mate with females. In both conservative and optimistic models, larger females had a greater probability of mating success compared to smaller crabs. The results from the 2013 and 1974 comparison clearly do not indicate a reduction in the evidence of successful matings, and in fact suggest an increase in observed mating success (Figure 2.16). In addition, more than 50% of large female crabs carry eggs (Figures 2.13, 2.14 and 2.15); this implies that red crabs do not all spawn at the same time (asynchronous spawner) (Morgan and Christy, 1995). From my recent dissection of female red crabs, I found evidence that mature female crabs can store sperm (pers. comm.-Bradley Steven-UMES). The comparison of 1974-76 observations to the 2013 observations of mating success also suggests that fishing has not had a negative effect on the mating success of large females. Crabs in estuarine waters are synchronous spawners to maximize their larval survivability due to temperature and predators (Morgan and Christy, 1995).Unlike those crabs, red crabs live in relatively stable environmental conditions; hence, it is reasonable to suggest that red crabs are asynchronous spawners. I also conclude that mating success is high given the evidence of female red crab scarring and their ability to do multiple mating and storing sperm. In summary, I observed no evidence of scarcity of large females to mate with large males given the evidence of female to male proportion for largest class, and high mating success probability in females.

4.3. Estimation of fishing mortality on males

In this study, the dynamics of the red crab population are depicted as the changes in the form of total mortality and fishing mortality throughout the years of the observational data. My estimates of life history parameters (M, K and CW^{∞}) have successfully described the observations in the 1974 data, although the M/K ratio that I used is in the upper-level estimate for a crustacean (Prince et al., 2014). The estimated values for CW^{∞} for males of 145 mm for the northern area and 154 mm for the southern area are reasonably similar to estimates from the 1974 study (Wigley et al., 1975), which estimated that male red crabs reach CW^{∞} of 150.

In general, red crabs in the northern area have experienced higher total mortality than in the southern area, as the fishery has historically exploited the northern area, and has only recently started fishing in the southern area. The level of fishing mortality in the northern area in 2010 was estimated at 0.59 and at 0.47 in

2012. In 2012, I also found that mean size of male crabs was larger than in the 2010 observation. Landing per Unit Effort (LPUE) as reported by NMFS-NEFSC decreased from 2010 to 2012 (SCS, 2013). These observations suggest that fisherman have started to retain larger crabs, and this practice has led to the decrease in LPUE. These findings hence can be credited to the fisherman's effort to decrease fishing mortality in order to increase the crab sizes. However, my observations from the 2010 and 2012 data indicate a relatively high exploitation rate, 0.73 and 0.68, respectively.

As a relatively new fishing ground, the southern area has experienced a lower fishing mortality compared to the northern area. The results from 2012 indicate that the exploitation rate was below 0.5, where F and M are similar, 0.20 and 0.21 respectively. Although the 2012-13 observations indicated a lower exploitation rate, this result should be taken cautiously since the observations were taken from more than 140 km apart. These findings suggest that the southern area itself may represent two different characteristics in terms of size distribution and level of fishing mortality, whereas the area near Hudson Canyon is similar to the northern area. This finding is consistent with the trend of behaviors that the fishery is expanding to the south in order to meet a market demand for larger size crab.

As F_{MSY} is still unknown, a ratio of fishing mortality and total mortality (exploitation rate) can be a useful measurement to generally assess current stock condition (Abowei et al., 2010), whether or not the fish stock is at a sustainable level of harvest. Referring to the assumption that sustainable yield is maximized when fishing and natural mortality are equal, hence the optimum exploitation rate is 0.5 (Gulland, 1971), the fishing level in the northern area clearly indicated a high level of exploitation. As for the southern area, the exploitation indicates an optimum level of harvest with exploitation rate ~0.5.

As my results are highly dependent on the CW frequency distribution, any effects that result in a different configuration of CW during the data collection would contribute to a bias or even inaccuracy in our CCA. It is noted that a video survey to estimate abundance was inaccurate due to avoidance by red crab compared to trawl survey (Wahle et al., 2008). As my study utilized two different gears (trawl and trap) to collect red crab, it is likely that the CCA will produce an over/underestimate of total mortality and lead to an inaccurate estimate of fishing mortality from one of the gears (Fischer and Wolff, 2006). In my analysis, the trawl distributions tended to produce a lower estimate of total mortality compared to the trap. Because CW distribution collected from fishing gear is also a function of recruitment and gear selectivity (Abowei et al., 2010), the trawl survey likely collected a wider range of CW distribution, while trap surveys likely produced a narrower distribution.

Another factor that contributes to the difference in sample collection is the difference in depth. Trawl surveys were conducted at various depths while trap surveys were more localized in the area where the male proportion was higher than female (Tallack, 2007). As sex is segregated by depth (Hastie, 1995), the CW distribution from a different depth will also be different. Hence, although my estimate of fishing mortality is relatively high for the trap fishery in the northern area, this result could only be because the data were collected from the fishing area with a limited depth range. Nevertheless, I believe that the fishery should be concerned since my estimated fishing mortality suggests an overfishing condition in the northern area.

Hence, based on these results, it appears that fishing pressure on the male red crab in the northern area should be reduced, with or without compensating a female harvest in the area.

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Table 2. 1. Descriptive statistics for carapace width (mm) in the northern area.

Year	Survey	Number	Mean	SD	Median	Var.	Mode	Range	IQR
2002	Pot	3173	94	9	95	88	98	77	11
2010	Pot	2735	94	7	94	52	95	50	9
2012	Pot	4446	100	9	101	74	102	68.08	11
1974	Trawl	508	99	28	108	782	116	123	35
2004-05	Trawl	1002	80	20	76	383	70: 115	112	29

Table 2. 2. Descriptive statistics for carapace width (mm) in the southern area.

Year	Survey	Number	Mean	SD	Median	Var.	Mode	Range	IQR
2010	Pot	4650	97	9	98	84	96: 105	68	14
2012-13	pot	5191	111	12	110	150	108	89.57	14
1974	Trawl	103	95	37	109	1352	110	122	43
2004-05	Trawl	363	87	19	85	345	80:116	90	27

Table 2. 3. Results of parametric (testing for mean and significance at the 0.05 level are indicated by *) and non-parametric tests (testing for median and indicated by the p-value) for males CW from different surveys and years in the northern area.

i/j	Trap 2002	Trap 2010	Trap 2012	Trawl 1974	Trawl 2004_05
Trap 2002		0.0001	<.0001*	<.0001	<.0001
Trap 2010	0.0001		<.0001*	<.0001	<.0001
Trap 2012	<.0001*	<.0001*		1.0000	<.0001
Trawl 1974	<.0001	<.0001	1.0000		<.0001
Trawl 2004_05	<.0001	<.0001	<.0001	<.0001	

Table 2. 4. P-value of non-parametric tests (testing for median value) for males CW from different surveys and years in the southern stock.

i/j	Trawl 1974	Trawl 2004-05	Trap 2010	Trap 2012-13
Trawl 1974		<.0001	<.0001	<.0001
Trawl 2004-05	<.0001		<.0001	<.0001
Trap 2010	<.0001	<.0001		<.0001
Trap 2012-13	<.0001	<.0001	<.0001	

Table 2. 5. Numbers of observed females to males, sex ratio, and proportion of males to females from trap survey in the red crab fishery.

Sex	North			South		
	2002	2010	2012	2010	2012	2013
Female	1739	652	1122	1802	295	312
Male	3173	2735	4446	4650	3578	1613
F: M ratio	0.5	0.2	0.3	0.4	0.1	0.2
Sex proportion (F: M)	1 : 1.8	1 : 4.2	1 : 4.0	1 : 2.6	1 : 12.1	1 : 5.2
Chi-Square	419	1281	1984	1257	2783	879
Pr > ChiSq	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001

Table 2. 6. Numbers of observed females to males, sex ratio, and proportion of males to females from trawl surveys in the red crab fishery.

Sex	North		South	
	1974	2004-05	1974	2004-05
Female	535	2247	202	1020
Male	508	1002	103	363
M: F ratio	0.9	0.4	0.5	0.4
Sex proportion (M: F)	1 : 1.1	1 : 2.2	1 : 2.0	1 : 2.8
Chi-Square	0.6989	477	32	312
Pr > ChiSq	0.4031	<.0001	<.0001	<.0001

Table 2. 7. Logistic regression (additive) model coefficients for female mating success (egg bearing female only). The p-value indicates its significant effect to the model. The model was implemented using Generalized Linear Model (GLM) in R with CW and location/area as explanatory variables.

Variables	Estimate	Std.Error	z value	Pr(>|z|)
CW	0.035	0.006	5.537	<.0001
North	-4.031	0.628	-6.422	<.0001
South	-4.808	0.670	-7.181	<.0001

Table 2. 8. Logistic regression coefficients of the conservative model for northern, southern, and combined portions of the stock for female red crab in 2012.

North	Estimate	Std.Error	z value	Pr(>|z|)
Intercept	-4.134	0.680	-6.082	<.0001
Carapace width	0.036	0.007	5.263	<.0001
South				
Intercept	-4.169	1.714	-2.432	0.015
Carapace width	0.029	0.017	1.744	0.0811
Combined				
Intercept	-3.558	0.615	-5.787	<.0001
Carapace width	0.029	0.006	4.679	<.0001

Table 2. 9. Logistic regression coefficients of the optimistic model for northern, southern, and combined portions of the stock for female red crab in 2012.

North	Estimate	Std.Error	z value	Pr(>|z|)
Intercept	-3.583	0.669	-5.357	<.0001
Carapace width	0.046	0.007	6.623	<.0001
South				
Intercept	-4.256	1.891	-2.251	0.024
Carapace width	0.058	0.019	3.063	0.002
Combined				
Intercept	-3.966	0.623	-6.365	<.0001
Carapace width	0.051	0.006	7.917	<.0001

Table 2. 10. Logistic regression model coefficients for the southern portion of the stock for female red crab in 2013.

Conservative	Estimate	Std.Error	z value	Pr(>|z|)
Intercept	-0.35144	1.43084	-0.246	0.806
Carapace width	0.0052	0.01272	0.409	0.683
Optimistic				
Intercept	8.71953	5.22433	1.669	0.0951
Carapace width	-0.04206	0.0451	-0.933	0.351

Table 2. 11. Total mortality and fishing mortality estimates for the northern area.

Year	Total Mortality (Z)	Fishing mortality (F)	Exploitation rate (E)
1974	0.22	0.00	0.00
2004-05	0.28	0.06	0.22
2010	0.80	0.59	0.73
2012	0.69	0.47	0.68

Table 2. 12. Total mortality and fishing mortality estimates for the southern area.

Year	Total Mortality	Fishing mortality	Exploitation rate (E)
1974	0.21	0.00	0.00
2004-05	0.31	0.09	0.30
2012	0.42	0.20	0.49
2012-2013	0.32	0.11	0.33

Figure 2. 1. Map of the southern and northern area for all surveys.

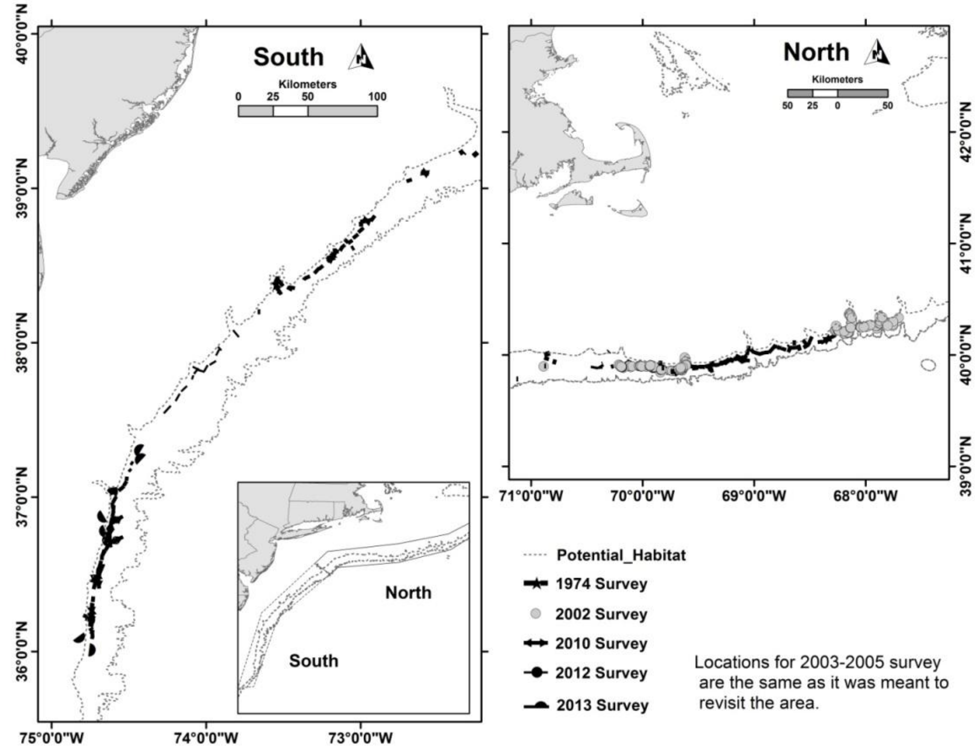


Figure 2. 2. Carapace width frequency distributions for male red crabs in the northern portion of the study area.

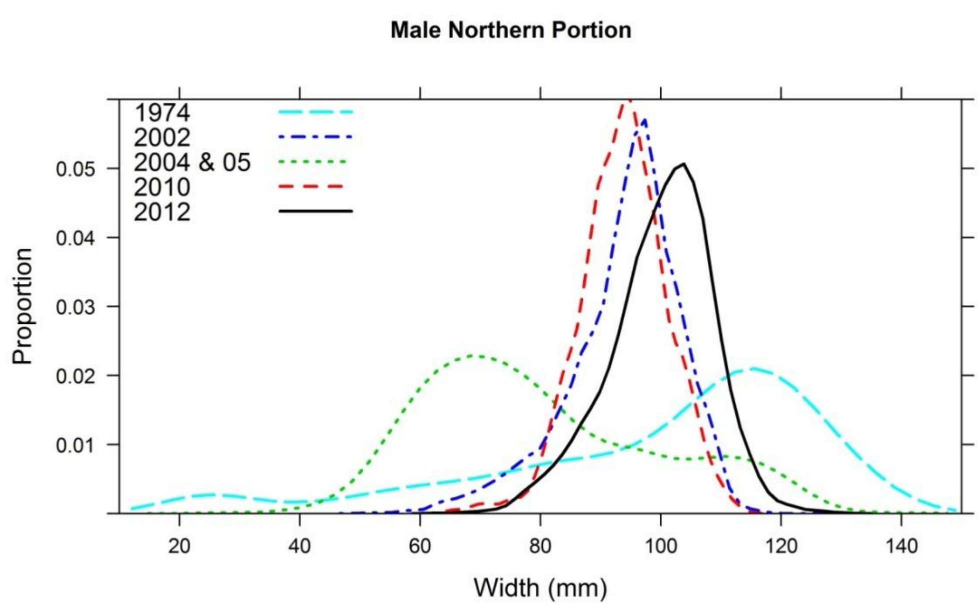


Figure 2. 3. Carapace width frequency (in mm) distributions for male red crabs in the southern portion of the study area.

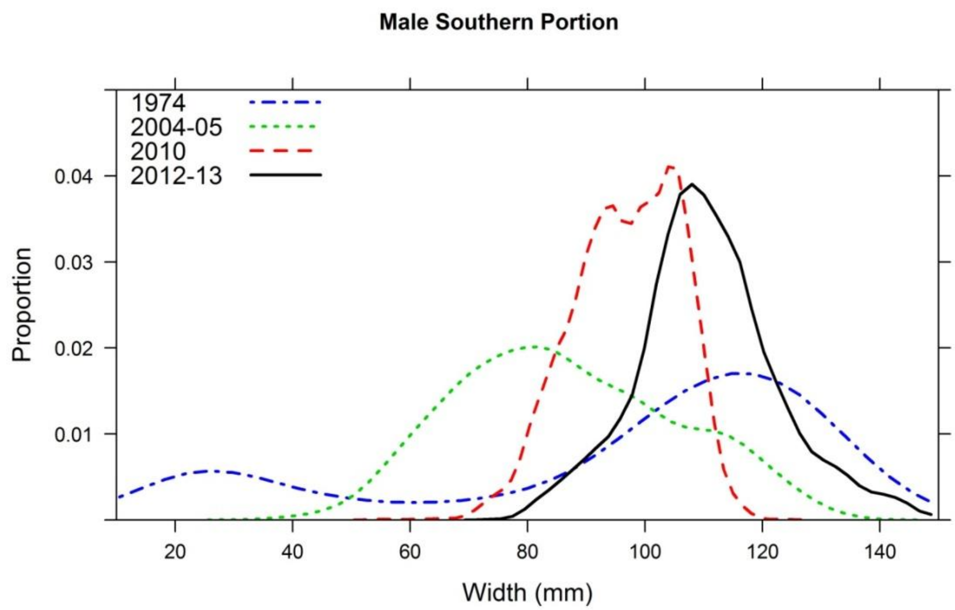


Figure 2. 4. Survey locations from trap and trawl survey. The locations for 2004-05 are the same as 1974 survey.

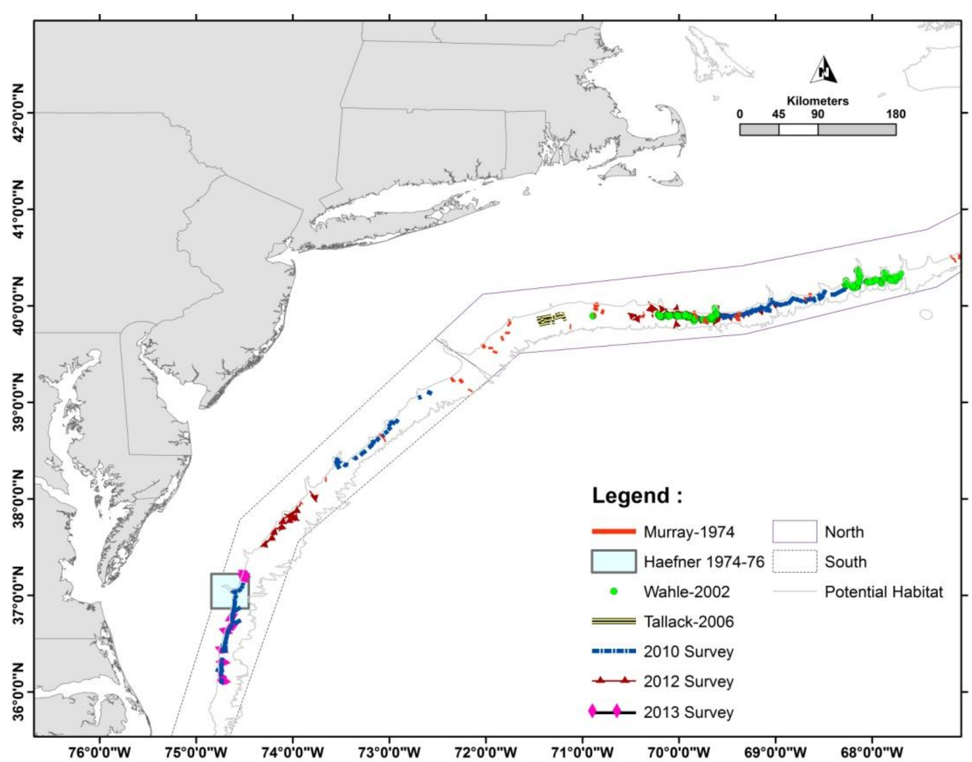


Figure 2. 5. Catch characteristics of the trap survey data.

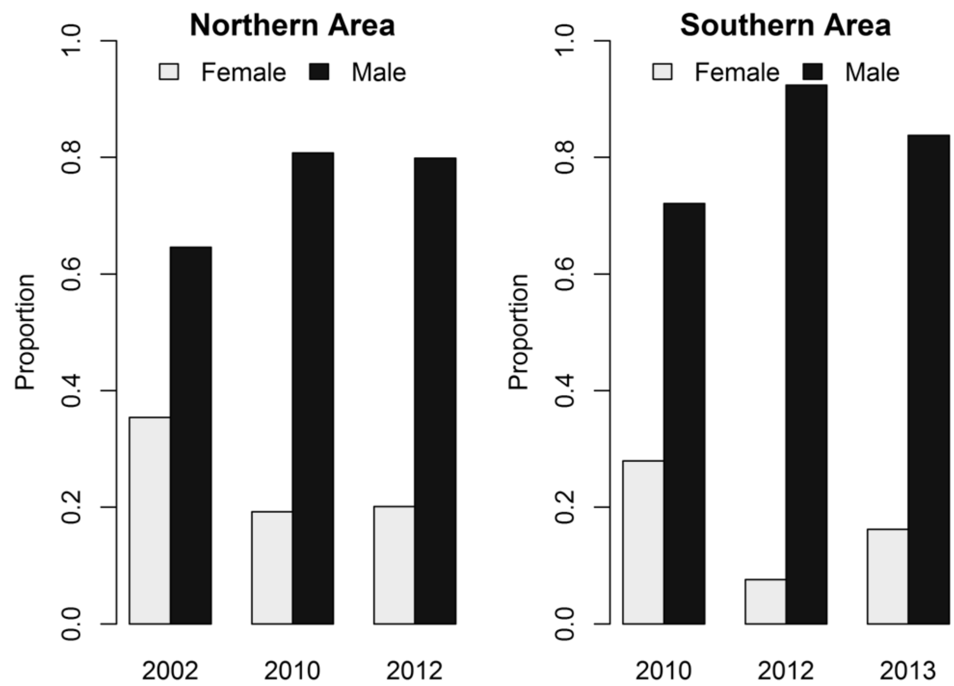


Figure 2. 6. Catch characteristic of the trawl survey.

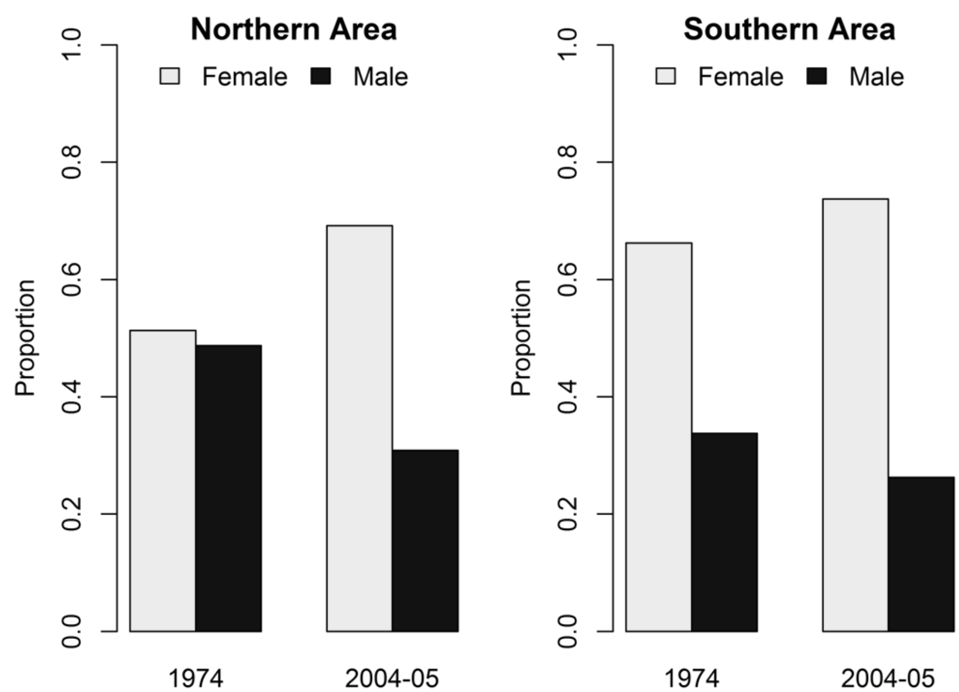


Figure 2. 7. Female to male proportion for northern area of the stock for trap survey.

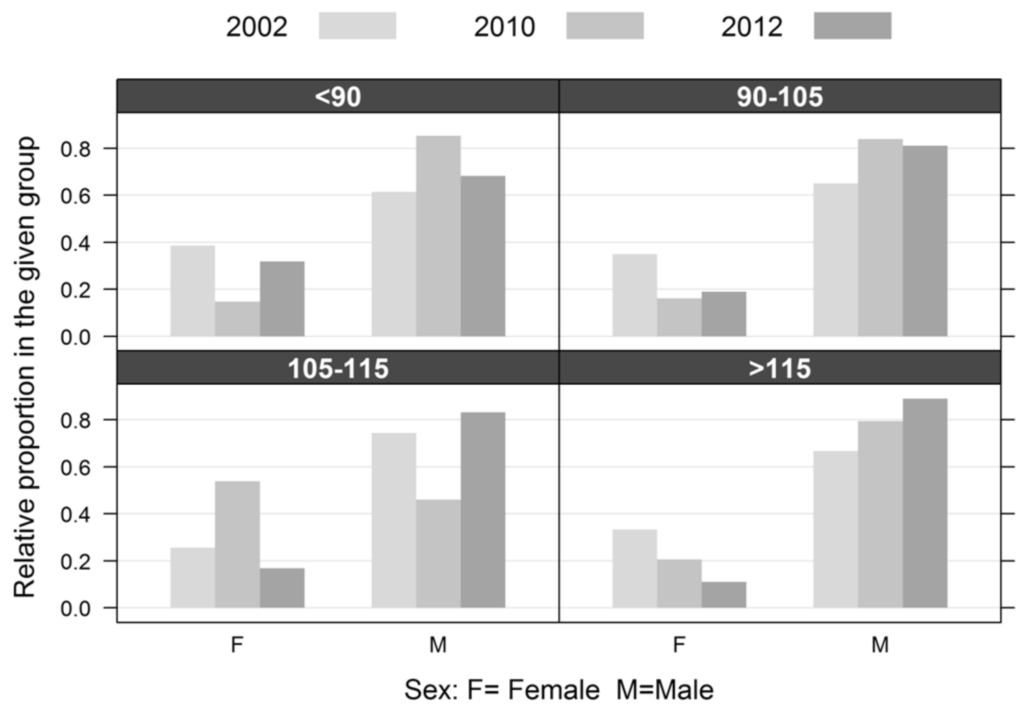


Figure 2. 8. Female to male proportion for southern area of the stock for trap survey.

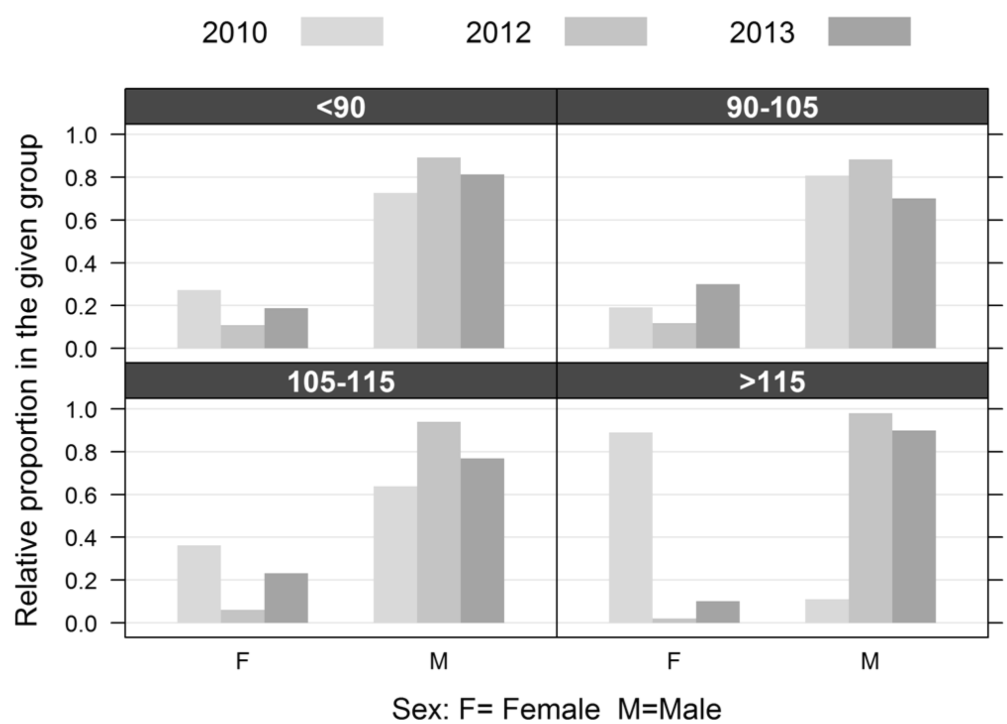


Figure 2. 9. Female to male proportion for northern portion of the stock for trawl survey.

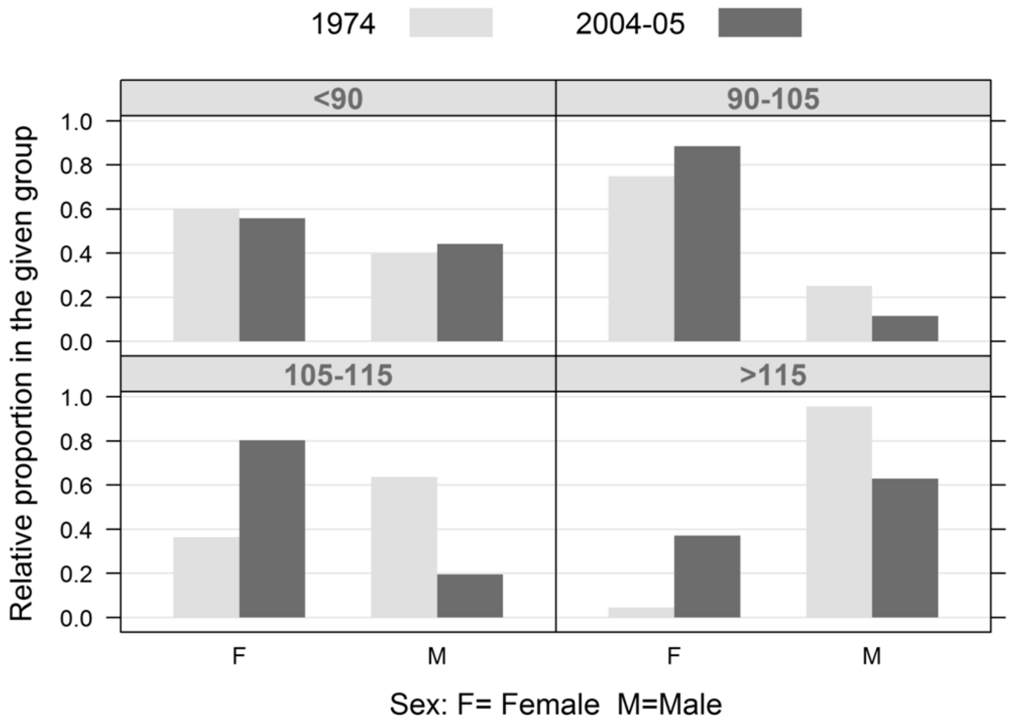


Figure 2. 10. Female to male proportion for southern portion of the stock for trawl survey.

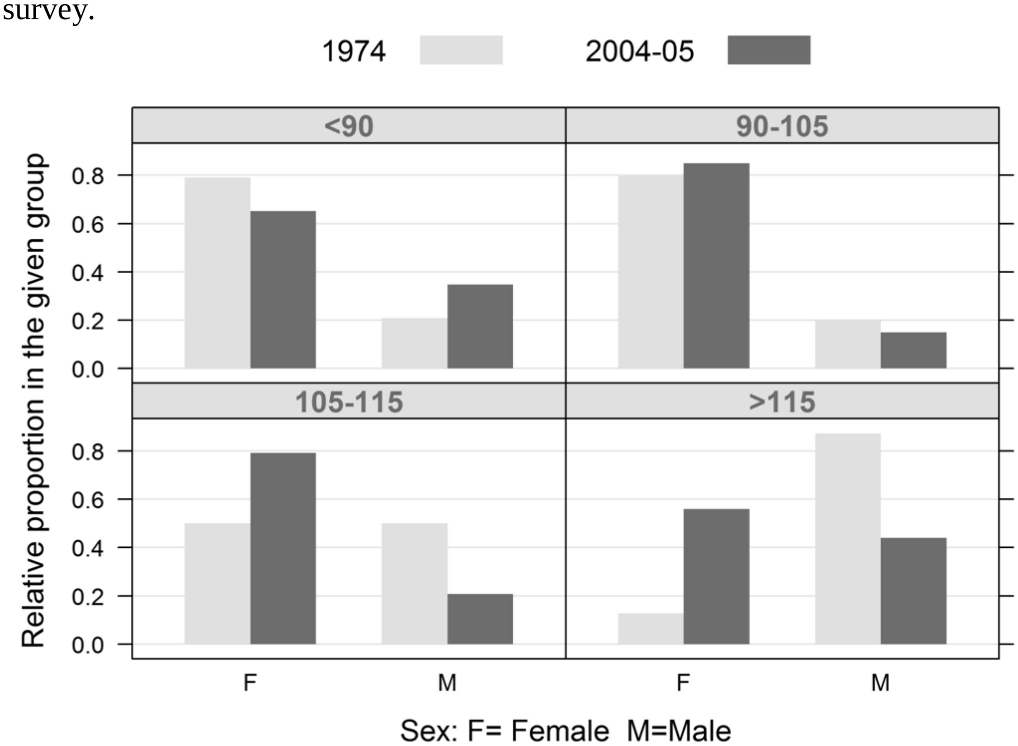


Figure 2. 11. Carapace width distribution from Tallack (2007). The light grey indicated the overlaid value of female and male.

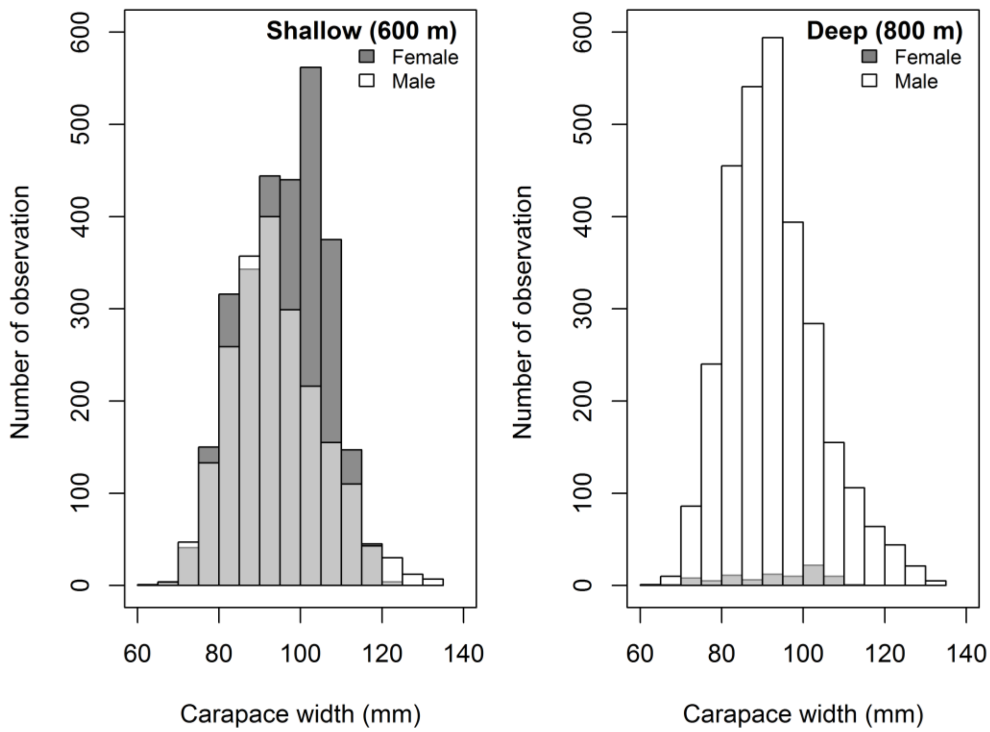


Figure 2. 12. Sample size of females in 2012 survey.

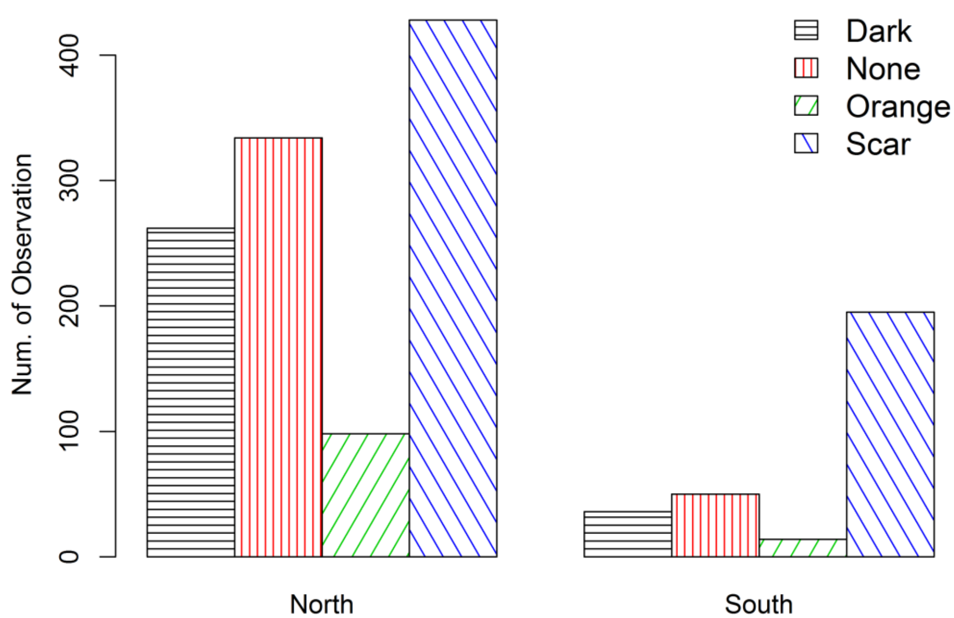


Figure 2. 13. Probability of mating success and 95% confidence interval of conservative model from 2012 survey.

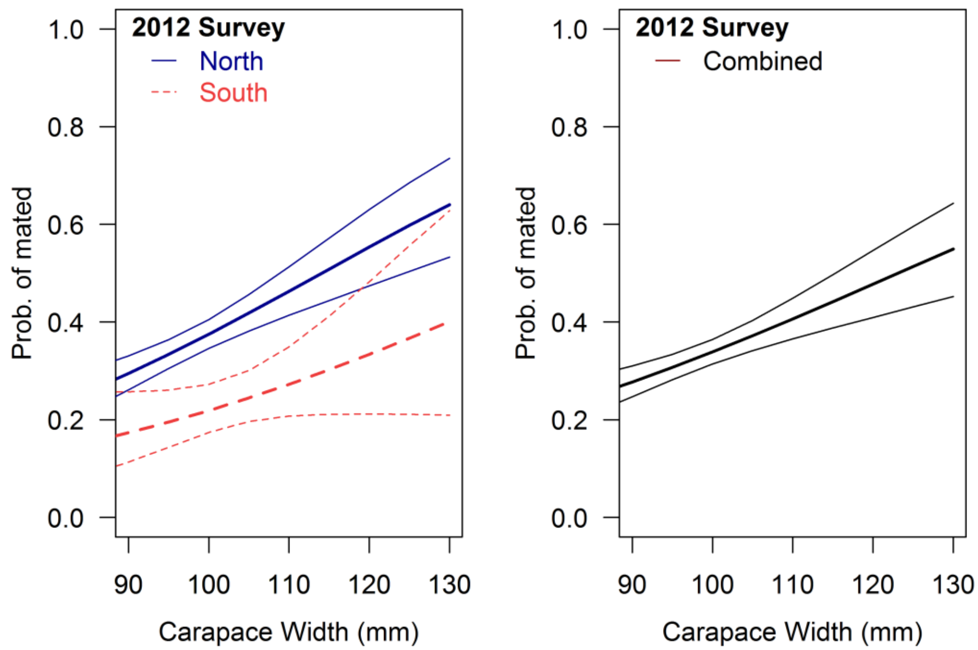


Figure 2. 14. Probability of mating success and 95% confidence interval of optimistic model from 2012 survey.

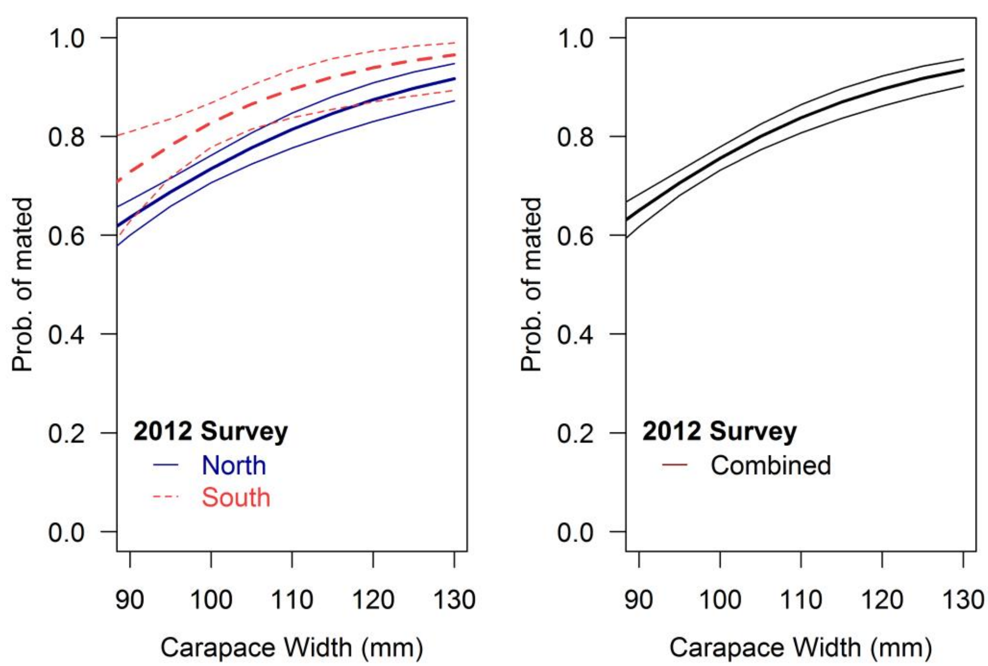


Figure 2. 15. Probability of mating success and 95% confidence interval from 2013 survey for southern stock and the sample size.

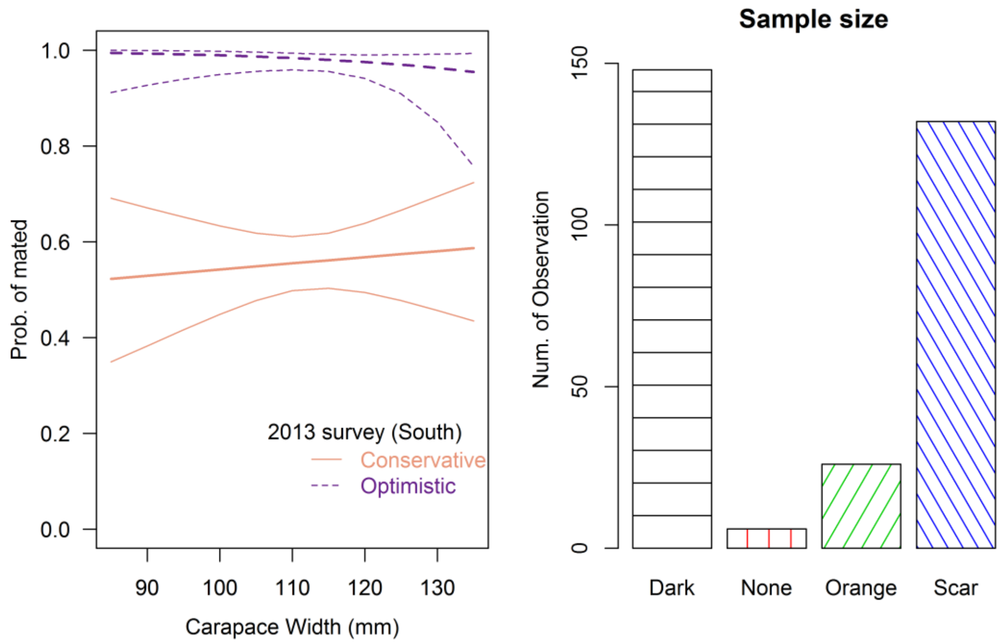


Figure 2. 16. Probability of mating success and 95% confidence interval from 1974-75 and 2013 survey for southern stock.

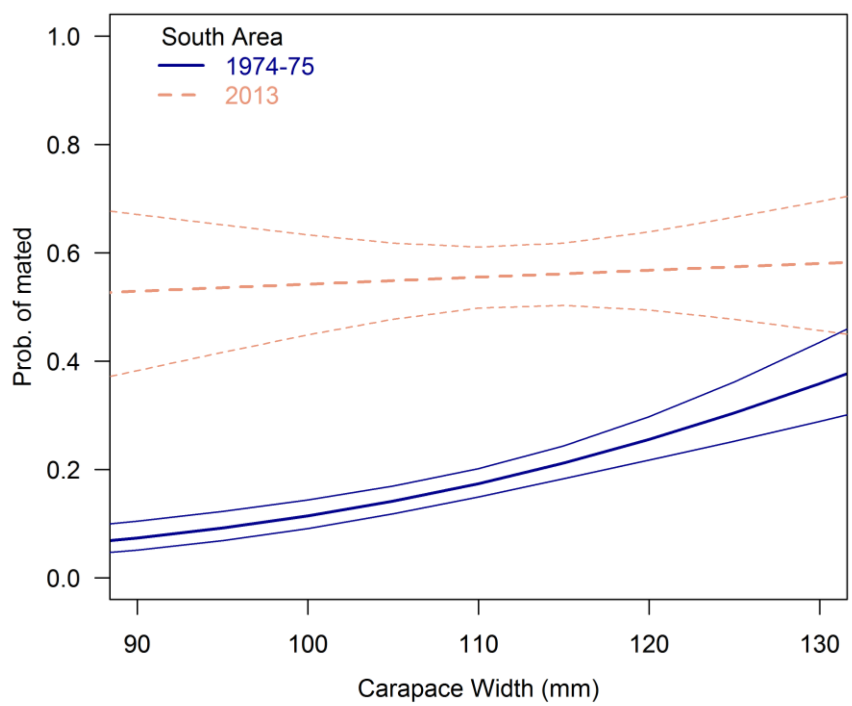


Figure 2. 17. Age-length key from length structure model for north and southern area.

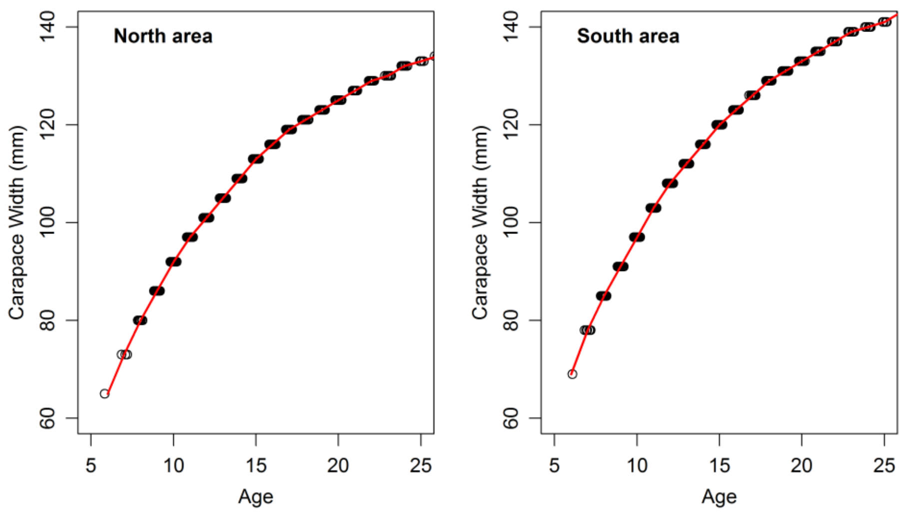


Figure 2. 18. Total mortality and 95% confidence interval estimation for northern area.

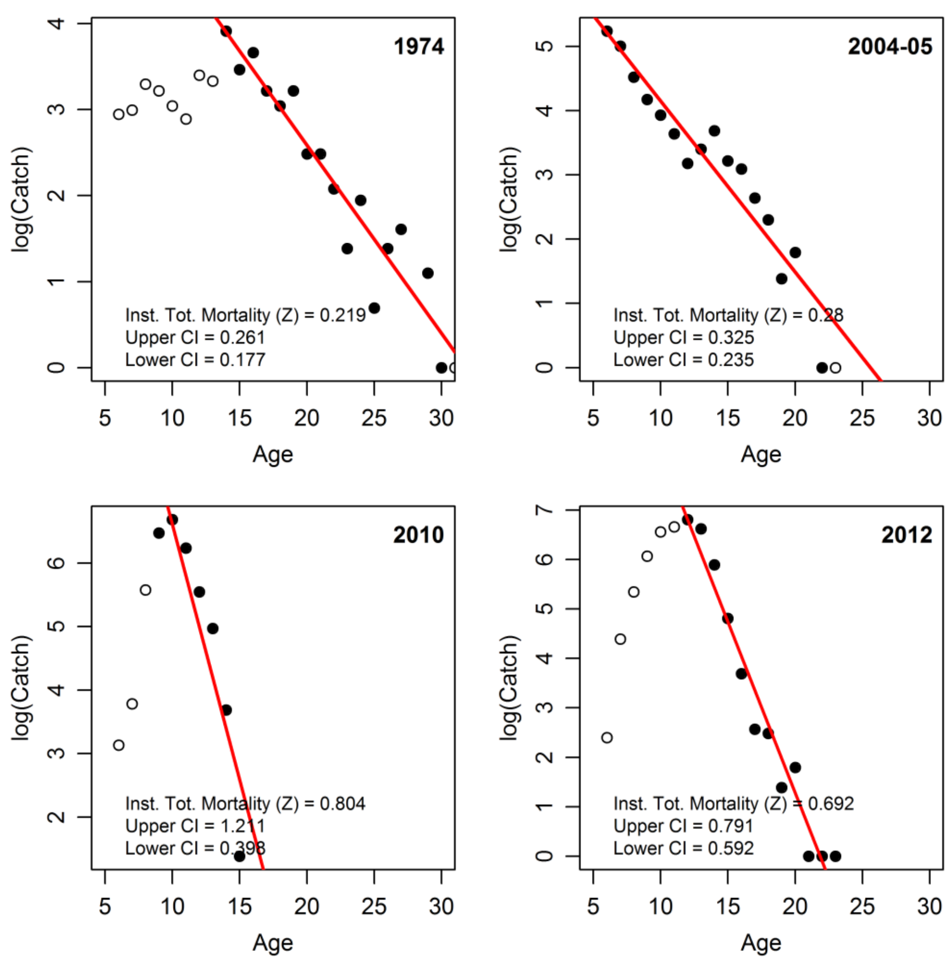
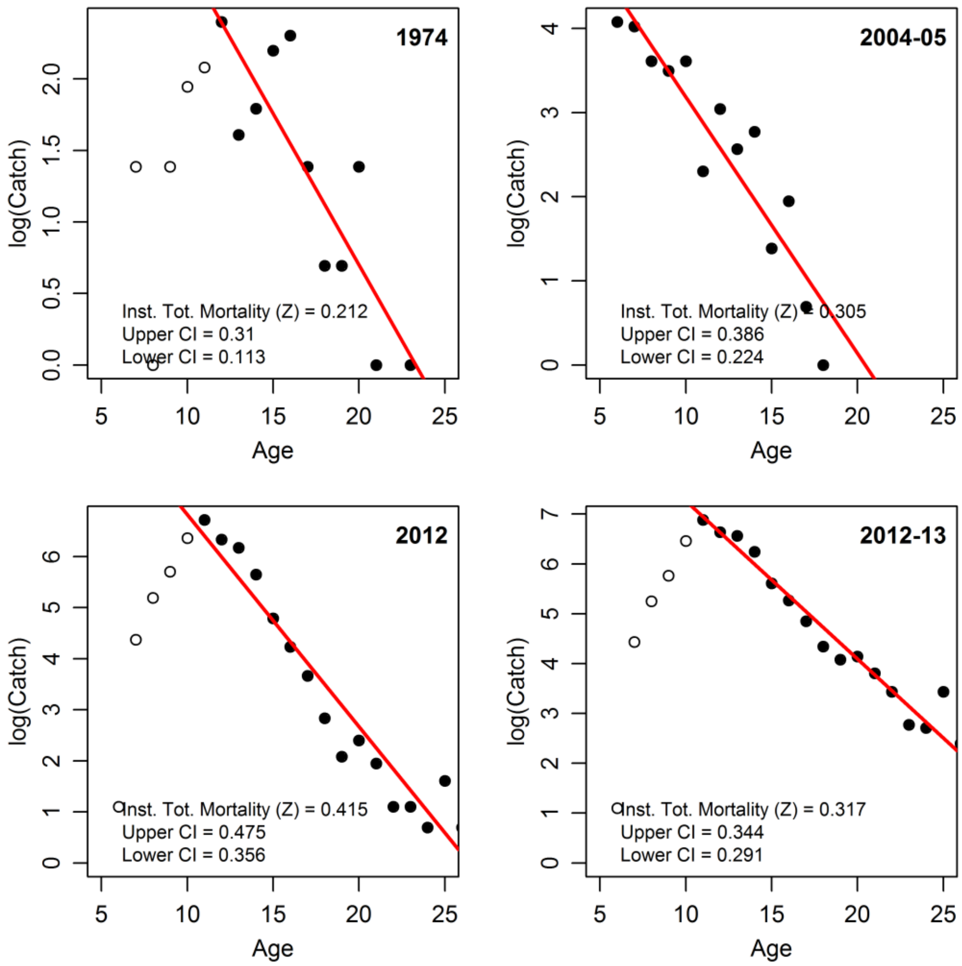


Figure 2. 19. Total mortality and 95% confidence interval estimation for southern area.



Manuscript-3

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Effects of harvesting on the stock biomass of the red crab (*Chaceon quinquedens)* population in the Northwest Atlantic

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Effects of harvesting on the stock biomass of the red crab (*Chaceon quinquedens*) population in the Northwest Atlantic

ABSTRACT

The deep-sea red crab has been harvested since the 1970s with the fishery limited to male red crabs only. In 2009, the Marine Stewardship Council certified it as sustainable. In this study, I separated the red crab population in the northwest Atlantic into two sub-stocks, with Hudson Canyon as a biogeographic barrier dividing the population along the upper continental slope off New England and the mid-Atlantic. After estimating discards and dead discards, I utilized a biomass dynamic model to estimate biological reference points including maximum sustainable yield (MSY) and other properties (F_{MSY}, B_{MSY}, and E_{MSY}) for each portion of the stock (northern and southern).

The geographic area available for the northern stock is about twice the area available for the southern stock. I estimated densities of 0.612 and 1.375 ton/ km^2 for the northern and southern stocks, respectively. I estimated that the MSY for the northern stock is higher (1129 mt) than for the southern stock (669 mt). The total MSY is estimated to be 1797 mt; this level is slightly higher than the current Total Allowable Landing (TAL) that was set at 1775 mt. The F/FMSY from both areas indicates that overfishing is not occurring in the most recent year (2012), although the model indicates a higher fishing mortality than did the previous stock assessment estimate. The B/BMSY ratio indicates an improvement compared to the previous year (2011) in both areas, and indicates that both areas are not currently overfished. The

estimated density of red crabs in the southern area is almost twice the density in the northern area, and this results in higher CPUE values in the southern areas as compared to the northern areas.

1. Introduction

Deep sea red crabs (*Chaceon quinquedens*) have been harvested since the 1970s in the northwest Atlantic. The fishery is limited to landing male red crabs only (Wahle et al., 2008). It was certified as sustainable according to Marine Stewardship Council (MSC) standards by Scientific Certification Systems, Inc in 2009 (SCS, 2011). Only incomplete landings data are available for the first decade of this fishery (Wahle, 2006; Wahle et al., 2008). Fishing Vessel Trip Reports (VTR) for red crab were initiated in 1994, but were only required after 2002, hence any landings reported prior 2002 must be treated as minimum landings. Two fishery-independent surveys of the red crab resource in the northwestern Atlantic were conducted in 1975 (Wigley et al., 1975) and 2003-2005 (Northeast Data Poor Stocks Working Group, 2009). Red crab stock assessments were conducted twice in the last three decades, 1977 and 2006 (NFSC, 2006; Serchuk, 1977).

In order to maintain the MSC certification for the deep sea red crab fishery, the clients/fishermen were required to develop and support data collection so that annual stock assessments could be conducted in the future (SCS, 2011). The stock assessment of a data-limited fishery is very challenging and often results in high uncertainty (Jiao et al., 2011). The term "limited" can mean lack of information regarding the stock or lack of credible data. Landings per unit effort (LPUE) has been the only time series index of relative abundance available for deep sea red crab (NFSC, 2006). As a result, a bias is likely to occur in the interpretation of this index, as the dead discarded biomass that represents removals for the stock (the younger age group) is not accounted for (Quirijns and Poos, 2008). However, this information can now be estimated from the results of recent analyses of discarding and discard mortality in the red crab fishery (Syuhada, 2014 (MS#1 and #2 of this dissertation), and when combined with landings and effort data, a biomass dynamic model (BDM) can be implemented as the primary assessment tool. This model can be applied with or without an assumption of equilibrium stock condition. The relationship between catch and the relative index of abundance, Catch per Unit Effort (CPUE), is crucial to fit the model. The total catch or removals is the sum of male landings and dead male discards, while CPUE is based on the sum of male landings and male discards divided by effort.

To fit the time-series data into the model, the non-equilibrium method can be implemented using process error or observation error only, or combining both terms (Calder et al., 2003). This procedure is very important when implementing the BDM, since the deterministic model is not realistic as the sources of variation in biomass are not only a function of biomass but also fishing (Laloë, 1995). Three models are widely used (Pella-Tomlinson, Graham-Schaefer and the Fox model) to estimate maximum sustainable yield (MSY). Although the MSY value was introduced as a target in the fishery in single-species assessment, new studies incorporating environmental condition and multi-species interactions suggested that MSY should be set as a limit in the fishery (Mace, 2001). Due to the important nature of MSY, recent stock assessments for the red crab fishery have focused on estimating this value using several methods based on trawl surveys in 1974 and 2003-2005 and other species (*Geryon. maritae*) (Allen et al., 2010; Chute et al., 2008).

This study will contribute to provide the fishery with an index of abundance (CPUE), stock biomass trajectory, level of exploitation, and the estimation of reference points through the implementation of a biomass dynamic, surplus production model using almost 20 years of VTR data acquired from National Marine Fisheries Service (NMFS).

2. Methods

2.1. Discard estimation.

In order to estimate the amount of discards given the amount of landed crab, I used VTR data from 1996 to 2013 from six boats participating in the fishery (Figure 3.1). I separated the fishing area into north and south portions based on Hudson Canyon as a bio-geographic barrier (see Syuhada, 2014, MS#1 this dissertation) (Figure 3.1 and 3.2). To obtain an appropriate estimate of discard to landing ratio, eliminating erroneous outliers in the data, I used the landings data that did not exceed 40 metric tons (MT), as the maximum legal landings are 35 MT. Further, after I calculated a ratio of reported discards to landings, I then used only the ratios that did not exceed 6:1. These two steps essentially filtered out of the data set reports of zero or near zero discards, and reports of unrealistic landings. I then calculated a mean discard to landings ratio for each area.

To calculate the amount of discards for the given landings, I multiplied the VTR-reported total landings by area by the estimated mean ratio of discards to landings. In addition, to estimate male discards only, I utilized the mean ratio of the estimated male to female discards from my previous study (Syuhada 2014, MS#1 of this dissertation). I calculated the mean ratio of the estimated male to female discard from three years of data (2002, 2010 and 2012) for the northern area and two years (2010 and 2012) for the southern area.

2.2. Biomass dynamic model input

I used catch and CPUE as the input to implement the biomass dynamic model. The yearly catches (C_t), as removals from the stock, were calculated based on the reported landings (L_i) and estimated dead discarded (Dd_i) male red crabs.

$$C_t = \sum_{i=1}^{n}(L_i + Dd_i)$$

Where i is index of summation. Since the VTR recorded only the days of absence from the dock, I made an adjustment to calculate the effort for every trip. For the boats that are from the northern area (RI and MA), and fishing in the northern area, the day of fishing is calculated as days of absence minus 2 days and minus 3 days if fishing in the southern area. This correction is necessary to avoid underestimation of CPUE. The effort is expressed as number of traps utilized during the trip. It is calculated as number of days fishing multiplied by 600 (number of traps allowed in the fishery). The CPUE for the given year is calculated as follows:

$$CPUE_t = \frac{\sum_{i=1}^{n}\left(\frac{L_i + D_i}{effort}\right)}{n}$$

Where (D_i) is total male discard and n is the number of observations. Note that the catch used in the CPUE is the landings + all male discards, not just dead discards.

2.3. A non-equilibrium surplus production model and density estimate

Since the catch and index of abundance (CPUE) for red crab are available, a biomass dynamic model becomes an appropriate tool to conduct a stock assessment (Hilborn and Walters, 1992). This model assumes that the recent biomass (B_t) is related to previous biomass with removals due to natural mortality and fishing (Smith et al., 2007). This deterministic model can be expressed as:

$$B_{t+1} = B_t + rB_t\left(1 - \frac{B_t}{K}\right) - C_t$$

Where r is the intrinsic growth rate of the population, C_t is the catch and K is the carrying capacity. In this study, I used a continuous observation of catch and CPUE, 1996 to 2012 and 2001 to 2012 for northern and southern area respectively. Since we have a good time series for both areas and more certainty in our input (C_t and $CPUE_t$), I utilized a stochastic model incorporating process error, assuming that variability in stock is affected by factors not included in the model (Meraz-Sánchez et al., 2013). The model is written as:

$$B_{t+1} = \left[B_t + rB_t\left(1 - \frac{B_t}{K}\right) - C_t\right]\exp(\mathrm{E_t})$$

Where: $\exp(\mathrm{E_t})$ is the process error term and follows a normal distribution $N(0, \sigma_E^2)$. This method reduced the amount of parameters to be estimated since initial biomass (B_0) is calculated as:

$$B_0 = \frac{CPUE_0}{q}$$

Where: q is the catchability coefficient. The predicted yield/catch is calculated as F (fishing mortality at the given year) times predicted biomass at the given year. The equations for management measures are given below:

$MSY = \frac{rK}{4}$	$F_{MSY} = \frac{r}{2}$	$B_{MSY} = \frac{K}{2}$
$E_{MSY} = \frac{2 * MSY}{q * K}$	$CPUE_{MSY} = \frac{MSY}{E_{MSY}}$	

Where: MSY is maximum sustainable yield, F_{MSY} is the fishing level at which MSY is achieved, B_{MSY} is the biomass at MSY, E_{MSY} is the effort at which MSY will be achieved, and $CPUE_{MSY}$ is the CPUE at MSY. I utilized three software packages (ASPIC, Microsoft Excel and R) to check the consistency of my results and explore different approaches in the stochastic model (observation error) during the data analysis. The parameter estimation was conducted using least square method.

To estimate the density (biomass/area) for the north and south areas, I calculated the area from the depth of 250 to 1000 meters from the Hague line in the northern area to 35° 56' 38.4" N in the southern area. Since the red crab fishing ground covers a large area, I utilized Albers Equal Area Conic projections to estimate the total area. The density estimation is expressed as B_{MSY}/area, K/area, and $B_{current}$/area.

3. Results

3.1 Fishing history

Landings of male red crabs for the northern and southern areas peaked in 2004 at 1211 mt, and have been steady at about 600 mt in the northern area for the last seven years (Table 3.1 and Figure 3.4). In the southern area, landings of male crabs peaked in 2011 at 1004 mt, increasing from about 300 mt in the early 2000s, and in 2011 were 508 mt (Table 3.2 and Figure 3.4).

The VTR data in the northern area indicated a declining trend in the ratio of discards to landings from 1996 to 2006 and an increasing trend from 2006 to 2012 (Figure 3.3). For the southern area, although there was an irregular up and down pattern from 2006 to 2012, I observed an increasing pattern in the ratio of discard to landing from the entire data set. I found that the mean ratios of discard to landing were 0.575 and 0.840 for northern and southern areas, respectively. In addition, I found that the mean ratio of male to female discards in the northern area is higher than in the southern area, 0.79 and 0.46 respectively (Syuhada, 2014, MS#1). Finally, I estimated the amount of dead discards based on my recent studies (Syuhada, 2014, MS#1 and MS#2 this dissertation) and a previous study (Tallack, 2007) which was 5% of total discards. My estimates of the amount of total discards, male discards and dead male discards are indicated in Tables 3.1 and 3.2, and Figures 3.4 and 3.5. In general, dead discard males were about 1% of landings, with the southern area indicating a slightly lower dead discard ratio that the northern area.

The catch and the index of abundance (CPUE) varied from year to year for both northern and southern areas (Table 3.1 and 3.2). For the northern area, the highest catch occurred in 2004 (1226 mt) and the lowest catch in 1998 (58 mt) and there was a slight variation in catch at around 549 – 760 mt from 2006-2012 (Figure 3.6). In the southern area, the catch has an overall increasing trend from 2001 until 2011 with the mean catch of 604.5 mt and maximum catch of 1014 mt in 2011 (Figure 3.7). However, there are some years where the catch dropped from the previous year (e.g., the catch dropped from 496 mt in 2002 to 300 mt in 2003 and from 709 mt in 2008 to 357 mt in 2009.

3.2 Biomass dynamic model and density analysis

The non-equilibrium biomass dynamic model was used to estimate management parameters for the red crabs in the northern and southern portions of the stock. The intrinsic growth rate differs in the north and the south. It was estimated to be 0.62 and 0.49 for north and south, respectively. Similarly, the northern area has a higher K (7282 mt) than does the southern area (5350 mt) (Table 3.3). As a result, the northern area also has a higher MSY (1129 mt) than that for the southern area (669 mt). The total MSY from both areas was estimated at 1797 mt; this estimate was calculated by adding the MSY estimates from the northern and southern areas (Table 3.3). Although the northern area has a higher MSY, the $CPUE_{MSY}$ in the northern area is lower than that in the southern area, 0.0057 and 0.0064 for north and south respectively. I found a higher F_{MSY} and E_{MSY} in the northern area as compared to the southern area and that to reach the MSY in the northern area, the fishermen need to expend more than twice as much effort (traps) as in the southern area, but this is primarily because the northern area is almost twice as large as the southern area, 6789 km^2 versus 3872 km^2.

In the northern area, I observed a mixed upward and downward trend of F/F_{MSY} ratio from 1996 to 2009 and a relatively stable ratio since then (Figure 3.5). In 2009 to 2012, the F/F_{MSY} ratio seems rather constant at about 0.5. The lowest F/F_{MSY} ratio was recorded in 1998 (0.052), and the highest was 0.68 in 2004. Overall, F/F_{MSY} ratio in the northern area fishery is always less than one, indicating that overfishing has not been a problem in the northern area. For the southern area, The F/F_{MSY} ratio shows an increasing trend from 2001-2008 (Figure 3.7). The smallest F/F_{MSY} ratio was about 0.17 in 2001, and it increased and reached a peak in 2008 at 1.20, indicating an overfishing condition. The F/F_{MSY} ratio then decreased to 0.38 in 2012. Overall, the southern area showed a higher F/F_{MSY} ratio than did the northern area during the study period.

The B/B_{MSY} ratio in the northern area has negative correlation to its F/F_{MSY} ratio; the B/B_{MSY} ratio increased when F/F_{MSY} ratio decreased, essentially the stock biomass decreased when fishing mortality increased. The B/B_{MSY} ratio was below one from 1998 to 2000 (0.98, 074 and 0.77). It started to increase from 2001 to 2007, decreased in 2009 and has been relatively stable above one since then. In the southern area, the B/B_{MSY} ratio decreased to the lowest level at 0.87 in 2008, indicating an overfished condition (B/B_{MSY} is less than one), then started to increase in 2009 and continued that trend through 2012 (Figure 3.7). Again, the stock biomass decreased in response to higher levels of fishing mortality, but then also increased when fishing mortality was reduced to less than F_{MSY}.

CPUE in the northern area fluctuated from 1996 to 2012 with mean CPUE of 0.008 ton/trap. I observed three cycles of CPUE fluctuation in this study. The lowest

CPUE occurred in 1999 and 2000 at about 0.004 ton/trap, and the highest CPUE was 0.014 ton/trap in 2003 (Table 3.1). CPUE in the southern area exhibited an increasing and decreasing trend as well. In 2001, the CPUE was very high at 0.021 ton/trap, and it gradually decreased until 2008. The CPUE improved from 2009 until 2012 based on my results.

For the southern area, the surface area was 3872 km^2, whereas in the northern area there was 6774 km^2 (Table 3.4). I used this area to estimate the density of red crab (Figure 3.2). From the density analysis (B_{MSY}/area), I found that the southern area was higher (0.691 mt/km^2) than the northern area (0.538 mt/ km^2). In the southern area, I found that the density in 2012 (1.375 mt/km^2) was higher than the density in the northern area (0.612 mt/ km^2).

4. Discussion

In the red crab fishery, fishing operations occur in a very specific area where the proportion of males to females is higher, typically 600 to 800 meters depth (Tallack, 2007). The fishery primarily targets male crabs larger than 114 mm (Wahle et al., 2008). Hence, fishing mortality in the red crab fishery is highly selective with respect to the location and size of the animal. The fishery in the northern area started more than four decades ago, while the fishery in the southern area is less than two decades old. Over time, these disturbances will affect the population in terms of size structure and eventually alter the sustainable yield for a target species (Law, 2000). As a result of these factors, I observed spatially different characteristics in catch and mean carapace width of port sampling over the recent year (Figure 3.8). These observations are the rationale for my analysis to separate the northern and southern portions of the stock to conduct biomass dynamic modeling (BDM) (Figure 3.2). The BDM revealed good estimation values (constraints and optimality are achieved) of r, K and q to describe the characteristics of the stock in both areas.

If I assume that the environmental conditions where the target species lives are stable with relatively low to no variability (Steimle et al., 2001), the intrinsic growth rate in the northern area indicates a higher productivity than the southern area given the long history of fishing and higher fishing level. The VTR data indicated that the northern area has been fished long before the southern area, and then it appears that fishermen expanded their fishing grounds to the south (Figure 3.1). If the assumption holds, then I can conclude that the long history of fishing has made the northern area more productive than the southern area with the intrinsic growth rate of 0.62 per year.

It is appeared that the effects of fishing have reduced intraspecific competitions on food for deep-sea red crab that allowed a higher productivity in the area. The higher catch/removal rate in the northern area could have altered the life history characteristics of the animal by lowering intraspecific competition that allowed the crab to grow faster (Law, 2000), and reach maturity earlier, (Jorgensen, 1992) if maturity is dependent on the size of the animal. In addition, the density estimate, which is expressed in terms of biomass/area, indicated a low density in the northern area. Due to the larger fishing area and smaller size of the animal in the northern portion, this finding is reasonable.

Although there have been two stock assessments conducted during the last four decades since the fishery was started (NFSC, 2006; Serchuk, 1977), the management measures such as MSY and B_{MSY} have been highly uncertain. A recent report from Data-Poor Stock Assessment Working Group (DPSWG) in 2010 described various methods to define MSY. The estimated MSY ranged from 1098 to 3011 mt with the average of 2044 mt and standard deviation of 495 mt. I found that total MSY (northern and southern areas combined) to be 1797 mt; this result is higher than MSY under the emergency management plan that was set at 1700 mt, but it is very close to the recent total allowable landing (TAL) that is set at 1775 mt.

I found that F_{MSY} in the northern area (0.310) is higher than that in the southern area (0.242). However, the average fishing mortality in the northern area (0.13 ± 0.05) was lower than that in the southern area (0.17 ± 0.09). The fishing mortality results of my BDM analysis are lower than the F estimates from my Length-based Catch Curve Analysis (LCCA), where F was estimated to be 0.47 and 0.20 for the northern and southern areas, respectively. While the pattern of a higher F in the northern area as compared to the southern area is similar, the difference in the estimated F values is probably because of the greater number of assumptions in the LCCA analysis. I believe that the fishing mortality results of my BDM analysis to be the most reliable. With regard to the F estimate from the NFSC (2006) stock assessment (0.055 ± 0.008), my results consistently gave a higher prediction. I believe that this is because the previous F estimate considered only landings in relation to an estimated biomass from the previous stock assessment (2003-2005 survey). My estimate of F from the BDM indicates that overfishing is not occurring in either the northern or southern areas. The B/B_{MSY} ratio shows an improvement in stock biomass in both areas, and with the ratio above one, it indicates that these areas are not overfished, as well.

The red crab density estimates are particularly interesting, in that it appears that in 2012 red crab are almost twice as dense in the southern area as compared to northern area. This factor combined with the higher estimated catchability (q) in the south compared to the north (0.00000239 versus 0.00000157) should result in higher CPUE in the south as compared to the north. In 2012, the CPUE in the northern area was 0.0065, while the CPUE in the southern area was 0.0127. This result is confirmed by my personal observations at sea on board the fishing vessels where it takes almost twice as long the reach the trip target catch goal in the northern area as compared to the southern area.

Acknowledgements

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Table 3. 1. Male catch (removals or landings + dead discards), CPUE ((landings+ male discards)/effort), landing and discard for the northern portion of the stock.

Year	landing (mt)	Male discard (mt)	Dead Discard (mt)	Catch (mt)	Effort (# of traps)	CPUE (mt/trap)
1996	569	144	7	577	108600	0.0068
1997	327	83	4	331	55200	0.0097
1998	57	14	1	58	20400	0.0056
1999	405	102	5	410	147600	0.0043
2000	347	88	4	351	102000	0.0044
2001	877	222	11	888	163800	0.0069
2002	1056	267	13	1069	122400	0.0126
2003	1145	290	14	1160	132600	0.0141
2004	1211	306	15	1226	196200	0.0091
2005	1099	278	14	1113	144000	0.0104
2006	750	190	9	760	109200	0.0113
2007	542	137	7	549	89400	0.0114
2008	547	138	7	554	73200	0.0094
2009	660	167	8	669	147600	0.0062
2010	505	128	6	511	94800	0.0067
2011	621	157	8	628	136800	0.0063
2012	672	170	9	681	149400	0.0065

Table 3. 2. Male catch (removals or landings + dead discards), CPUE ((landings+ male discards)/effort), landing and discard for the southern portion of the stock.

Year	landing (mt)	Male discard (mt)	Dead Discard (mt)	Catch (mt)	Effort (# of traps)	CPUE (mt/trap)
2001	373	100	3	377	31800	0.0208
2002	491	132	5	496	49200	0.0143
2003	297	80	3	300	33600	0.0118
2004	515	138	5	519	82200	0.0085
2005	574	154	5	579	82200	0.0092
2006	812	218	7	820	146400	0.0073
2007	718	193	7	724	124800	0.0078
2008	702	189	6	709	174000	0.0056
2009	354	95	3	357	76200	0.0065
2010	907	244	8	915	150000	0.0083
2011	1004	270	9	1014	156600	0.0098
2012	508	137	5	513	52200	0.0127

Table 3. 3. Estimated parameters using the non-equilibrium biomass dynamic model.

Parameters	North 1996-2012	South 2001-2012
r	0.62	0.49
K (mt)	7282	5350
q	0.00000157	0.00000239
Reference points		
MSY (mt)	1129	669
F_{msy}	0.310	0.250
B_{msy} (mt)	3641	2675
E_{msy} (#traps)	197808	104484
$CPUE_{msy}$ (ton/trap)	0.0057	0.0064
Total MSY	1797 (mt)	

Table 3. 4. Density estimation from the northern and southern portion of the stock. K= carrying capacity.

Stock	Area (km^2)	Density (B_{msy}/area) (ton/ km^2)	Density (K/area) (ton/ km^2)	Current density (ton/ km^2)
North	6774	0.538	1.073	0.612
South	3872	0.691	1.382	1.375

Figure 3. 1. Fishing distribution of six boats from 1996 to 2012.

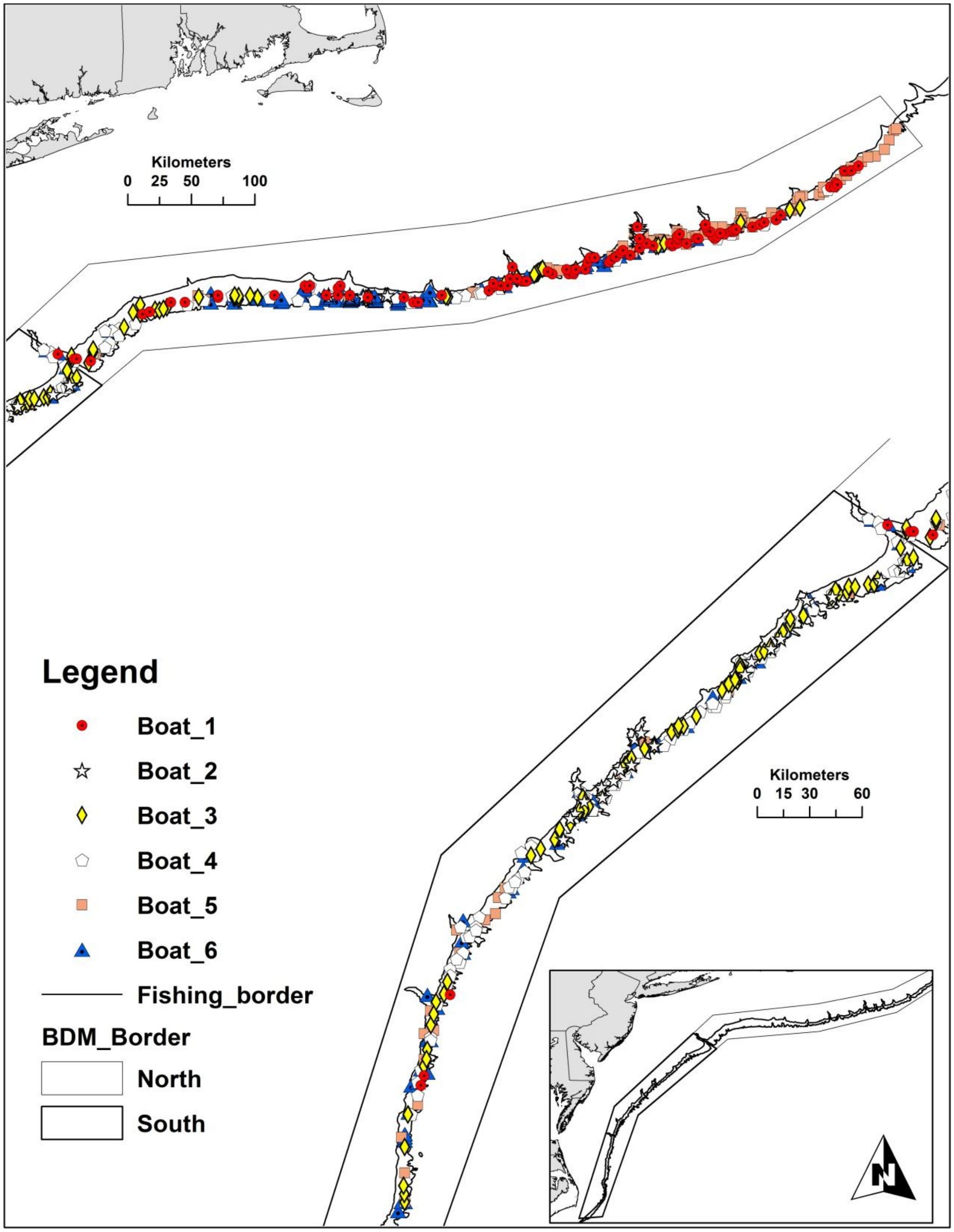


Figure 3. 2. Fishing area.

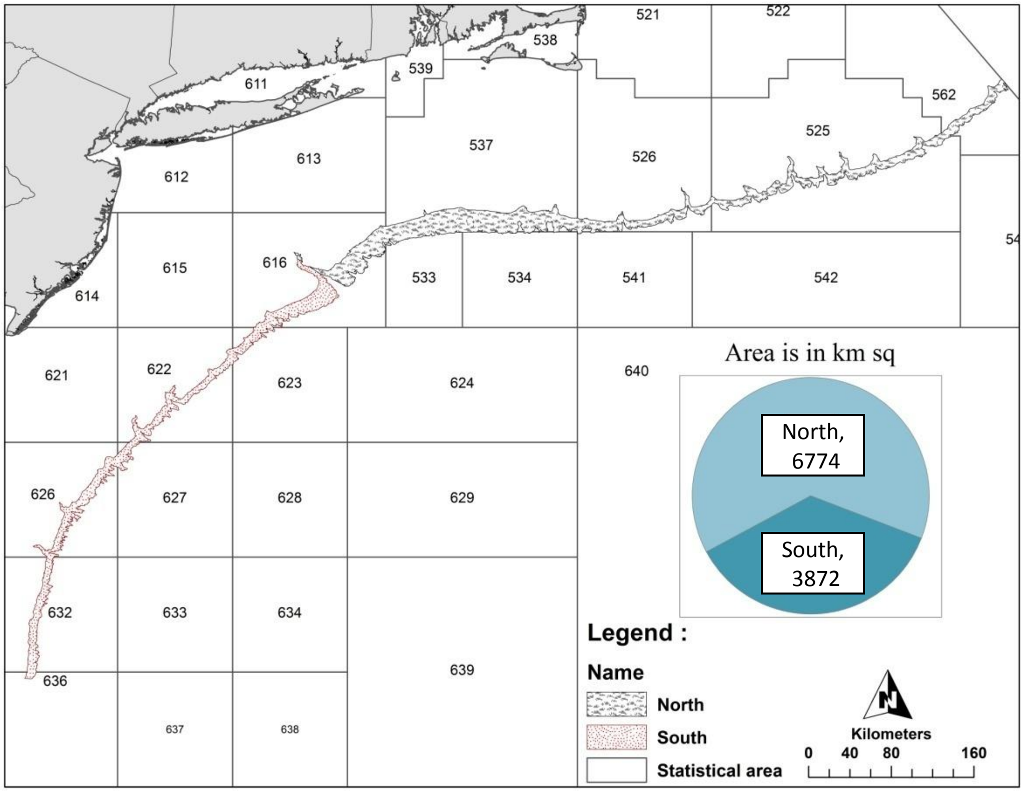


Figure 3. 3. Ratio of male landed to male discarded and its mean in a given year. The red line is the grand average of the observations.

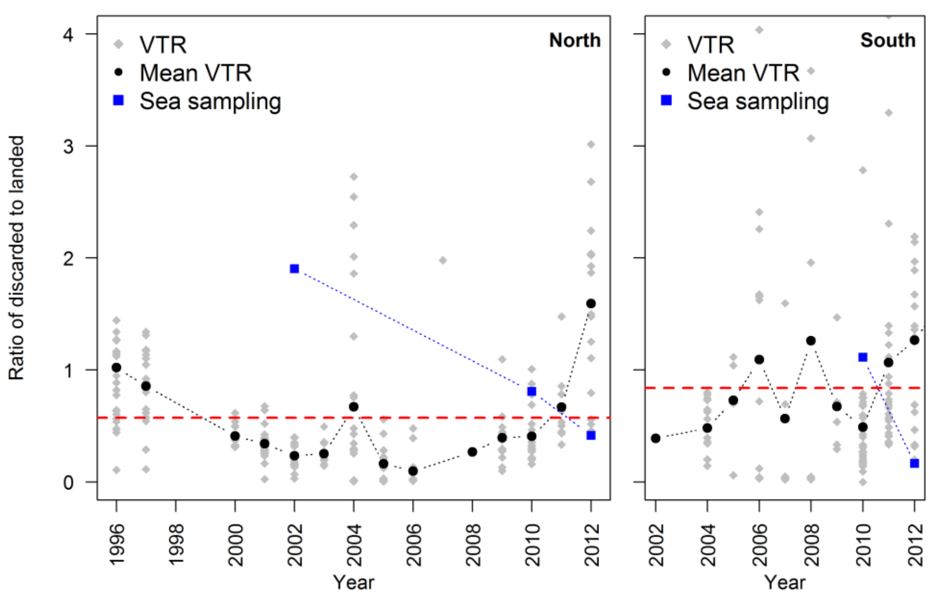


Figure 3. 4. Landings, total discards, male discards, and dead male discards from northern portion of the stock area.

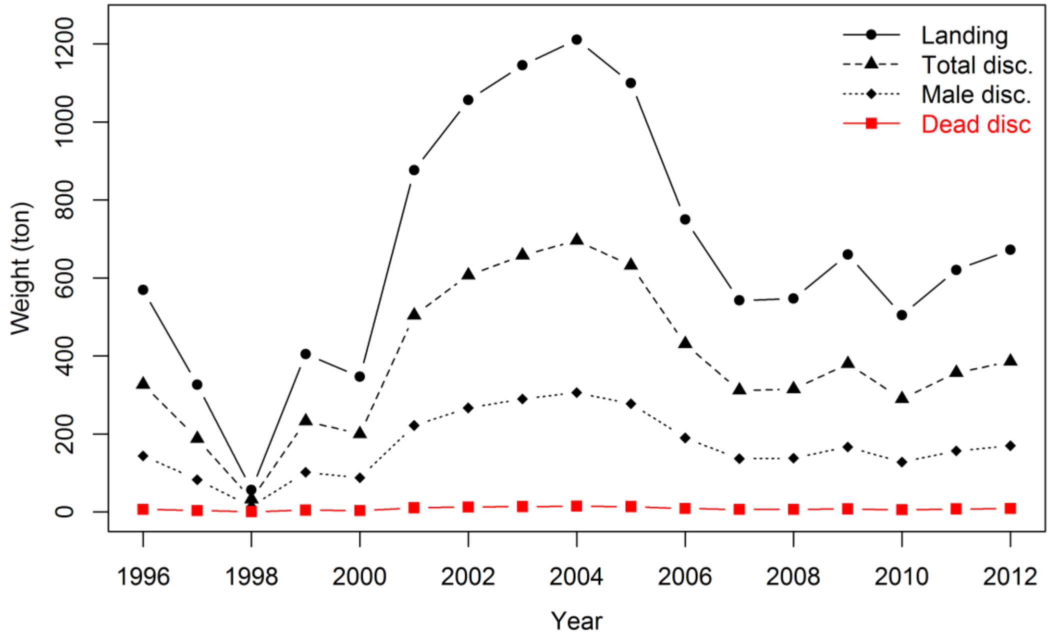


Figure 3. 5. Landings, total discards, male discards, and dead male discards from southern portion of the stock area.

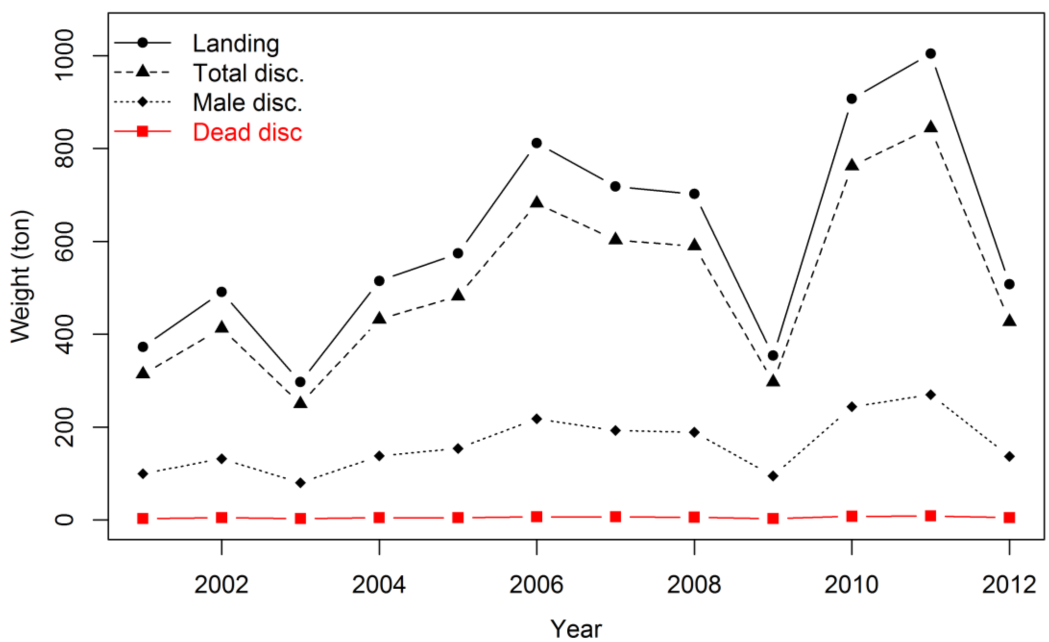


Figure 3. 6. Biomass dynamic model output from northern portion

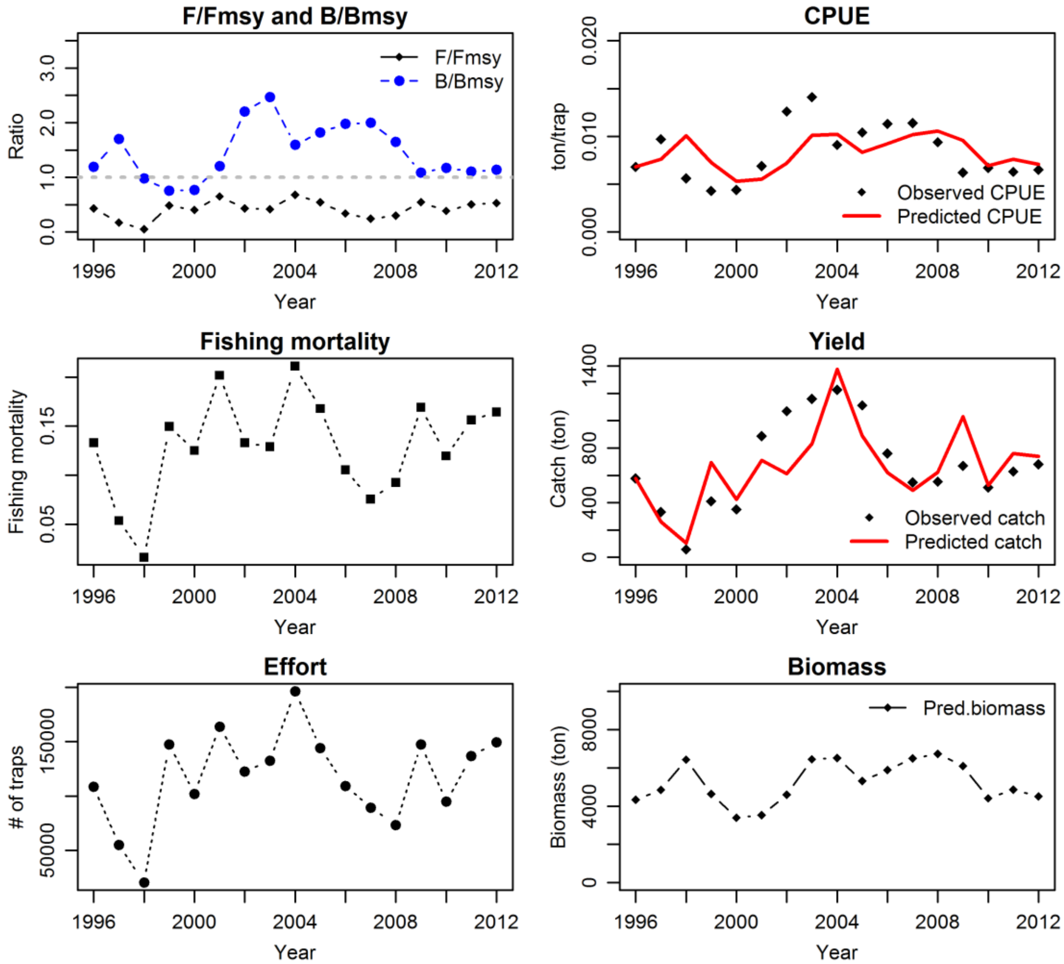


Figure 3. 7. Biomass dynamic model output from southern portion.

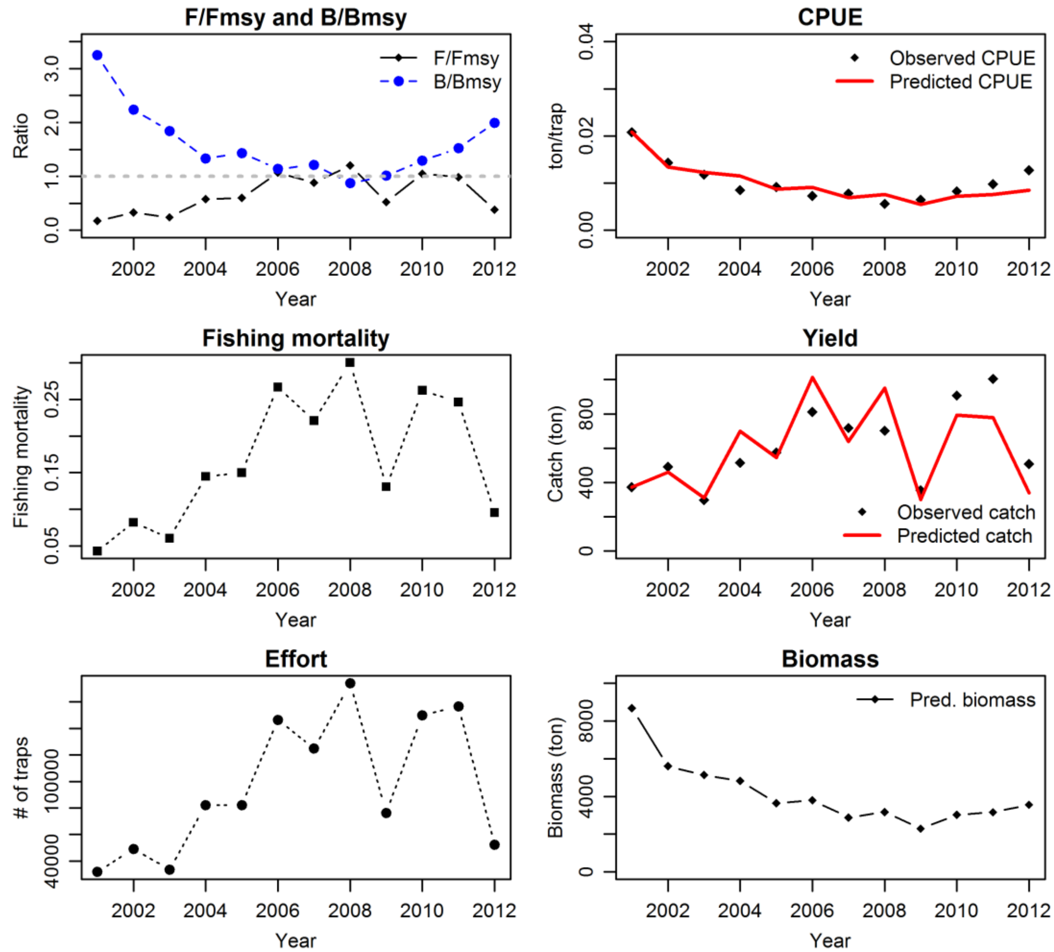
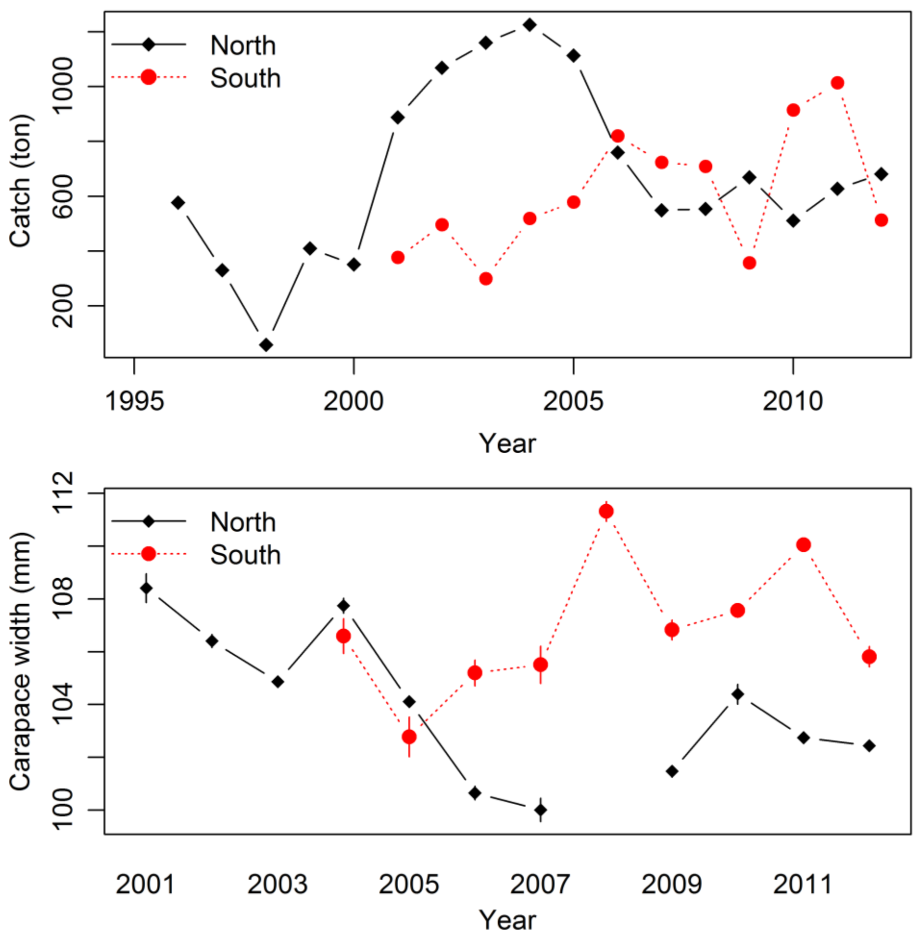


Figure 3. 8. Catch and mean carapace width of northern and southern portion of the stock.



Manuscript-4

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Preliminary assessment of the red crab fishery resource and the potential for supporting a commercial fishery in the Cape Verde Islands, West Africa

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Preliminary assessment of red crab fishery resource and the potential for supporting a commercial fishery in the Cape Verde Islands, West Africa

ABSTRACT

The deep-sea red crab (*Chaceon affinis*) resource in Cape Verde offers a potential economic export opportunity to the nation due to high quality of the meat, the size and its ability to survive for a long period in a holding tank, enabling it to be sold as live crabs. An exploratory fishing operation conducted in the vicinity of Santiago to Sal Island, Cape Verde, from February to April 2012 at depths of 300 to 970 m provided data for a preliminary assessment of this species as to its potential resource to be developed into an economically viable and biologically sustainable fishery.

The characteristics of the catch from this investigation found that the carapace width (CW) of males (mean=135 mm, *SD*=17 mm) are significantly larger than females (mean=122 mm, *SD*=15 mm). The largest male was 194 mm and the largest female was 159 mm. The number of females with eggs exceeded the number without eggs only at the 90 mm bin size, and then at smaller and larger CWs the number of females without eggs exceeded the number with eggs. In addition, the male to female ratio indicated a bias toward males with a CW greater than 105 mm. This would favor a male-only fishery for this species. However, the CPUE indicated a very low abundance of deep-sea red crab in the area, estimated at 1.1 kg/trap-haul with standard deviation of 0.33 kg/trap. Considering the low CPUE from the exploratory fishing, it is unlikely that this resource can support an economically viable and biologically

sustainable commercial fishery. This result is supported by the low estimated fishable biomass of 377 MT, and the corresponding low maximum sustainable yield (MSY) of 28 MT. However, the estimated biomass and MSY could be 18% higher with the addition of the area around Brava and Fogo Islands.

1. Introduction

The Cape Verde Islands are located in the eastern Atlantic and composed of 10 islands, which are divided into two subgroups; Barlavento and Sotavento (Jaenicke and Schütz, 1978; Menezes et al., 2004). The archipelago is part of the biogeographic region of Macaronesia (Lloris et al., 1991), and is a tropical oceanic system (Medina et al., 2007). Each island has a limited extension of coastal shelf, and therefore the islands are isolated by distance and depth, resulting in habitat fragmentation (Medina et al., 2007; Menezes et al., 2004) that may limit distribution and abundance of certain marine species (Öhman and Rajasuriya, 1998).

Deep-sea red crabs, *Chaceon affinis* (Milne-Edwards and Bouvier, 1894) was identified in the deep waters surrounding the Cape Verde Islands more than two decades ago (Manning and Holthuis, 1981). In 2003 and 2005 the Instituto Nacional do Desenvolvimento das Pescas (INDP) conducted initial scientific exploratory fishing in the deep waters surrounding the Islands of Boavista and Santiago with traps set on depth ranges of 300-500, 501-700, and 701-1000 meters (González and Tariche, 2009). In 2003, catches per unit effort (CPUEs) in Boavista were 0.3, 0.8 and 3.6 kg/trap-haul, respectively to the depth class. Moreover, in 2005, the traps were set in the same areas, and depth ranges, and the CPUEs were 0.8, 5.1 and 11.3 kg/trap-haul, respectively to the depth class. In Santiago Island, the 2003 CPUEs were 1.03, 0.19 and 0.08 kg/trap and in 2005 were 1.03, 1.60 and 0.48 kg/trap, respectively to depth class. Because of this work, INDP permitted a Spanish commercial fishing vessel to conduct commercial exploratory fishing trials in 2012 to further evaluate the potential for developing a commercial fishery for red crab.

A preliminary assessment of the Cape Verde red crab resource is very important prior to the development of a fishery there. Slow growth and a late maturity are important aspects that must be considered to evaluate potential yield for a red crab fishery. Relative abundance and distribution information of this resource will be used to estimate the yield that can be sustainably removed from the resource. Neglecting the life history aspects and abundance will negatively affect the resource stock and the fishery. The artisanal fisheries sector employs 79% of the total fishermen in Cape Verde and contributed 65% of national catch in 1992 (DANIDA and FAO, 1995). The industrial fishery is dominated by foreign fleets from the European Union and Japan, mainly fishing for tuna and other pelagic species (FAO, 2008). The red crab resource in Cape Verde may support a sustainable fishery, if the harvesting capacity is matched to the productivity of the resource and the fishery is actively managed.

In this study, I investigated the characteristics of the crabs caught during that exploratory commercial fishing effort in 2012. From these data, I have estimated the size at maturity for females (based on presence of eggs) and sex ratio based on carapace width (CW). I also provided the current CPUE from two areas and the distribution. From these analyses, I have made estimates of the fishable biomass and maximum sustainable yield (MSY).

Of the 22 different *Chaceon* crabs worldwide (Manning and Holthuis, 1989) only five species have been commercially exploited: *Chaceon quinquedens* (Wahle et al., 2008), *Chaceon maritae* (Melville-Smith, 1988a), *Chaceon affinis* (Robinson, 2008), *Chaceon macphersoni* (Groeneveld et al., 2013) and *Chaceon fenneri* (Carvalho et al., 2009). Two species of red crabs have been reported to inhabit Cape

Verdean waters, *Chaceon maritae* and *Chaceon affinis* (González and Tariche, 2009), and *Chaceon affinis* is more abundant than *Chaceon maritae*. *Chaceon affinis* is distributed at depths from 300 to 1600 meters (Castro et al., 2010; Fernández-Vergaz et al., 2000; Hastie, 1995; Lopez Abellan et al., 2002; Pinho et al., 2001; Robinson, 2008; Tuset et al., 2011).There is no record of commercial harvesting of *Chaceon affinis* in Cape Verde; however, there is an indication that this species could be a fishery resource (Hastie, 1995; Pinho et al., 2001).

Among other existing red crab fisheries, *Chaceon maritae* and *Chaceon quinquedens* fisheries have been the largest and oldest fisheries ever recorded (Hastie, 1995). The existing fishery of *Chaceon affinis* in the Northeast Atlantic by United Kingdom and Irish vessels has declined in landings over recent years (Robinson, 2008). The highest landings were reported in 2003 (1132 ton), there were only 220 tons landed in 2006. Although landings were reported since 2000, there is no regulation regarding this species. The fishery utilizes two types of fishing gears, a static net or pots depending on the bottom type where they are fishing (Robinson, 2008).

Several scientific surveys for *Chaceon affinis*, (referred to as king crab in the eastern north Atlantic islands) have been conducted to study life history, biological aspects and its distribution in eastern North Atlantic islands (González et al., 1996; Lopez Abellan et al., 2002; Pinho et al., 2001); however, there is insufficient information to support a quantitative assessment of the abundance of this species. *Chaceon affinis* is reported to be relatively larger than *Chaceon maritae* and *Chaceon quinquedens* (Hastie and Saunders, 1992). Lopez Abellan et al. (2002) and Pinho et al.

(2001) found that the maximum size of males is larger than that of females, 189 and 165 mm, respectively. Females are more concentrated in deeper water (Pinho et al., 2001) and enter the mature stage at length 113 to 115 mm (Lopez Abellan et al., 2002; Pinho et al., 2001). These studies have mentioned the potential harvest of this species; however they have not offered an estimate of MSY for the resource. Only *Chaceon quinquedens* (Haefner, 1978; Wahle et al., 2008; Wigley, 1975) and *Chaceon maritae* (Melville-Smith, 1988a) provided reports of CPUE and estimates of fishable biomass and MSY for the resource. From these data and accompanying estimates of the fishable biomass habitat area, an estimate of red crab virgin stock density in the Cape Verde Islands is derived, and from this an estimate of maximum sustainable yield (MSY) from this resource is obtained.

2. Methods

A total of 57 trawls of traps were set during exploratory commercial fishing from February to April 2012 on board the FV Condor, a 30-m Spanish commercial fishing vessel that was permitted by INDP to conduct exploratory commercial fishing operations in the Cape Verde Islands. To match the analyses used in the previous survey (2003-2005) in my study, I use the term north area (equal to Boavista) and south area (Santiago). The FV Condor fished in the deeper waters surrounding Santiago, Maio, Boavista and Sal Islands (Figure 4.1). Each trawl included 400 individual traps baited with mackerel and soaked on the bottom for durations from 24 to 48 hours at depths ranging from 300 to 970 m. I used this depth range to define and calculate the fishing ground area for Sal, Boa Vista, Maio, and Santiago Islands as one entity, and Brava and Fogo Island as another possible entity. Minimum and maximum depths were recorded for every trawl of traps set during the survey. Since the nature of the survey was to generally assess the resource for its potential to enter the fishery, the fishing was conducted in a broad area. To supplement the lack of biological data obtained from this field investigation; I have gathered additional information about the fishery to the species level (*Chaceon affinis*) and genus level (*Chaceon*) such as natural mortality (M), range of potential habitat and density estimation. This information is used to provide a broader understanding of the potential for Cape Verde red crab resource to be developed into a commercial fishery.

To investigate potential differences in carapace width distributions (CW) between males and females in the north and south areas (Figure 4.1), I analyzed the mean (M), median (Md), standard deviation (SD) and size-frequency distributions using ANOVA, Kruskal-Wallis (K-W) and a two-tailed Kolmogorov–Smirnov (K-S) test respectively. In addition, the sex ratios based on CW were tested with chi-squared analysis. In an attempt to estimate the CW at 50% probability of maturity using the observation of egg-bearing females as indication of maturity, I used a simple visual inspection of the data, as the data did not follow the anticipated pattern of an increasing probability of observing eggs with increasing CW.

I calculated the CPUE for the north area, south area and both areas combined. The CPUE for the given area is calculated as follows:

$$CPUE_{north\ or\ south} = \frac{\sum_{i=1}^{n}\left(\frac{W_t}{\#trap\ used - \#trap\ lost}\right)}{n}$$

where (W_t) is total weight from one trawl and *n* is number of observations.

To estimate the fishable biomass, I assumed that there is a constant of proportionality, the catchability (q), that relates the CPUE in the trap fishery to the density (D) of red crabs available to the traps (Miller, 1990; Morgan, 1974; Ricker, 1975).

CPUE = q*D

Where :

CPUE is the catch (kg) per unit effort (trap haul)

D is density (kg/m^2)

q is the catchability

I used a trap CPUE data for red crab and an independent estimate of stock density from a population model, photo survey, or tag/re-capture study and used linear regression to estimate q. The product of the mean fishable stock density and the stock area obtained using GIS to estimate the area between the depth contours of 300 and 950 m provides an estimate of the fishable biomass. To estimate the MSY for the red crab, virgin fishable biomass of the Cape Verde Islands, I used Gulland's (1971, 1983) approximation of the surplus production model for a stock at carrying capacity. I assumed that the current biomass is a virgin biomass due to no fishing activity. The MSY for the given area is calculated as follows:

$$\mathrm{MSY} = 0.5 * \mathrm{M} * \mathrm{E_B}$$

Where:

E_B is the estimated virgin biomass

M is the natural mortality = 0.15 for red crabs.

3. Results

3.1. Potential habitat and fishing ground

In this study, the potential habitat for *Chaceon affinis* in Cape Verde was identified based on the shallowest and deepest depth ever recorded for this species (130-2050 m). As a result, I found that most of the waters surrounding the Cape Verde Islands had significant potential habitat for *Chaceon affinis* (Figure 4.1). Unfortunately, only some locations are suitable as fishing a ground; that is the waters surrounding the islands of Sal, Boa Vista, Maio, Santiago, Brava and Fogo Island. The islands in the northwest area (Santo Antao, Sao Vicente and Sao Nicolau) are not suitable as fishing ground given the very steep slope. Using the depth ranges of the fishing operations (300-950 m), the area of the fishing grounds surrounding the islands of Sal, Boa Vista, Maio, and Santiago is estimated to be 3013 km^2, whereas the area surrounding the islands of Brava and Fogo is estimated at 533 km^2.

The fishing locations next to Boavista and Sal Islands (north) were shallower compared to the location nearby Maio and Santiago Islands (south). The average of minimum depth was 448 and 656 m for north and south area, respectively (Table 4.1). The average of maximum depth was 567 and 792 m from north and south area, respectively. If I ignore this separation, the exploratory commercial fishing activity in this investigation has included water depths ranging from 315 to 970 m.

3.2. Catch characteristics and CPUE

A total of 2618 crabs, 2173 males and 508 females, were captured and measured during the fishing operations. In general, males (M=135 mm, SD=17 mm) were significantly larger than females (M=122 mm, SD=15 mm), (F (1, 2679) =

233.2, p < 0.0001). In addition, both K-W and K-S tests indicated a significant difference (p<0.0001) between males and females (Table 4.2 and Figure 4.2). Sex ratio based on CW showed a non-significant difference for the bin classes up to 100 mm (Table 4.3 and Figure 4.3), indicating equal numbers of males and females up to 100 mm.

I also found that males in the south area (M=139 mm, Md=140 mm, SD=18 mm) are significantly larger (p<0.0001) than males in the north (M=129 mm, Md=130 mm, SD=15 mm) in terms of mean and median (Table 4.2 and Figure 4.4.). Female red crabs in the north area (M=122 mm, Md=121 mm, SD=17 mm) were not significantly different in CW from females in the south area (M=122 mm, Md=122 mm, SD=11 mm), although the K-S test indicated a significant difference between these two groups (p=0.0005) (Table 4.2). In addition, although the mean CW of females is the same between the two groups, the females in the north area have wider SD than the females in the south area (Figure 4.5).

The number of females with eggs only exceeded the number of females without eggs at the 90 mm bin size (Figure 4.6). As a result, the proportion of females with eggs only exceeded 0.5 at the 90 mm CW, and decreased from that maximum at smaller and larger CWs. The proportion of females with eggs is very low at CWs less than 80 mm, but the sample size is also small, due to the size selective characteristics of the traps. This result suggests that the observation of females with eggs may not be a reliable predictor of maturity in red crabs in Cape Verde, but does suggest that females less than 80 mm are immature, and that females greater than 90 mm are mature.

The CPUE in the north area (*M*=0.95 kg/trap, *SD*=0.32 kg/trap) was lower compared to the south area (*M*=1.21 kg/trap, *SD*=0.29 kg/trap) (Table 4.6). The mean CPUE in the north area had a greater range than the south area with SD of 0.32 (Figure 4.7). The lowest CPUE was recorded in the north area (0.44 kg/trap), whereas the highest was recorded in the south area (1.77 kg/trap). The mean CPUE for the combined area in Cape Verde Island was 1.07± 0.33 kg/trap, which corresponds to 1.5 crabs/trap-haul.

3.3. Biomass and MSY estimate

The data available for the regression analysis are listed in Table 1, and includes the results of recent studies of red crab in the north and south areas of the western North Atlantic (Syuhada MS 1,2, 3, this dissertation), and data from Namibia (Melville-Smith, 1988b). The catchability coefficient (q) estimate as a result of the linear regression (Table 4.5) was 8557 (Figure 4.8). The estimated fishable biomass within the area between the depths of 300 and 950 m from Santiago to Sal Island of the Cape Verde Islands is 377 MT, based on a Cape Verde CPUE of 1.07 kg/trap-haul, and a fishable area of 3013 km^2. Moreover, the estimated MSY is 28 MT and this includes both males and females. However, the estimated biomass and MSY could be 18% higher by including the area within the Fogo and Brava Island, 443 and 33 MT for the estimated biomass and MSY, respectively.

4. Discussion

The characteristics of the catch from this study confirm the findings of the previous studies that males are significantly larger than female (Fernández-Vergaz et al., 2000; Lopez Abellan et al., 2002; Pinho et al., 2001). The male to female ratio indicated more males for CWs larger or equal to 105 mm. As a result, this favors a male-only fishery for the deep-sea crab off Cape Verde; however, my biomass estimate and predicted MSY are for males and females combined. A male-only fishery would have a smaller MSY. With regard to the egg-bearing female observations, the observations suggest that females smaller than 80 mm are immature and the females greater than 90 mm are mostly mature.

Although most of the previous investigations of *Chaceon* crabs have found them to occur in water depths ranging from 300 to 1600 m, *Chaceon affinis* have been found to inhabit waters from the depth of 130 to 2047 m (Biscoito and Saldanha, 2000). Hence, in this study, I calculated the potential habitat for red crabs in Cape Verde waters using the shallowest and the deepest occurrence ever recorded. The exploratory commercial fishing in this investigation used pots at depths from 300 to 950 m and resulted in a very low CPUE (1.1 kg/trap) compared with exploratory fishing for the same species in the Canary Islands, which resulted in catches of 5 kg/trap-day (González et al., 1996) and 4 kg/ trap (Lopez Abellan et al., 2002). Other studies in Azores found patchy catches of this species, where one area produced 1.5 crab/trap, and another area produced 15 crabs/trap (Pinho et al., 2001). Although I found a difference in CPUE between north and south areas, the different fishing depths may have affected the results, as the pots were set deeper in the southern area.

Studies of fisheries for other red crab species such as *Chaceon quinquedens* and *Chaceon maritae* have reported much higher CPUEs. *Chaceon maritae* fisheries in Namibia reported that CPUEs after several years of fishing (1980) was at 11.46 kg/trap-haul, and six years later at 9.29 kg/trap-haul (Melville-Smith, 1988a). In the New England red crab fishery (*Chaceon quinquedens*) CPUE was reported at 25 kg/trap in 1974 at the initiation of the fishery (Arana, 2000). In my recent study CPUE was 43 crabs/trap (males and females) or about 26 kg/trap-haul for the entire continental slope of the USA (Syuhada, 2014, MS#3). Considering the very low CPUE from the exploratory fishing reported in this investigation, it is very unlikely that this resource in Cape Verde can support an economically viable commercial fishery. The very small CPUE also results in a very low estimated fishable biomass (377 MT) and MSY (28 MT), further indicating that there is an insufficient abundance of red crabs to support a commercial fishery. However, the estimated biomass and MSY could be 18% higher assuming the same CPUE for the area within Brava and Fogo Island.

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Table 4. 1. Depth (meters) profile during the exploratory fishing in Cape Verde.

Area	Depth	Mean	SD	Median	Min	Max	Range
North	Min	448	146	368	315	722	407
	Max	567	192	463	390	970	580
South	Min	656	37	658	603	768	165
	Max	792	64	786	640	932	292
Combined	Min	547	150	603	315	768	453
	Max	674	184	749	390	970	580

Table 4. 2. Carapace width (CW) comparison based on sex and location. F= female, M= male, K-W = Kruskal-Wallis, K-S = Kolmogorov-Smirnov.

Sample	N. of Obs.	CW (mm) Mean	SD	Median	ANOVA (p-value)	K-W test (p-value)	K-S test (p-value)
F-North	334	122	17	121	0.79	0.46	0.0005
F-South	174	122	11	122			
M-North	998	129	15	130	< 0.0001	< 0.0001	< 0.0001
M-South	1175	139	18	140			

Table 4. 3. Sex ratio between male to female by CW size class. Asterisks indicate a significant different.

CW (mm)	Male	Female	Sex ratio (M/F)	Chi-square
55	1	0	-	
70	6	5	1.20	0.091
80	7	2	3.50	2.778
90	4	10	0.40	2.571
95	1	0	-	
100	52	48	1.08	0.160
105	66	21	3.14	23.276*
110	128	73	1.75	15.050*
115	126	42	3.00	42.000*
120	198	85	2.33	45.120*
125	160	46	3.48	63.087*
130	271	60	4.52	134.504*
135	261	42	6.21	158.287*
140	293	42	6.98	188.063*
145	198	17	11.65	152.377*
150	203	13	15.62	167.130*
155	81	2	40.50	75.193*
160	33	0		
165	5	0		
170	33	0		
175	20	0		
180	15	0		
185	8	0		
190	3	0		

Table 4. 4. Summary of CPUE from north, south and combined area.

Area	Num. of Obs.	Mean (kg/trap)	SD (kg/trap)	Min (kg/trap)	Max (kg/trap)	Range (kg/trap)
North	30	0.95	0.32	0.44	1.67	1.23
South	27	1.21	0.29	0.6	1.77	1.17
Combined	57	1.07	0.33	0.44	1.77	1.33

Table 4. 5 . CPUE and density from The US and Namibia

Data	CPUE (kg/trap)	Density (kg/m^2)
US north	6.5	0.00061
US south	12.7	0.00138
Namibia	2.65	0.00067

Figure 4. 1. Locations of exploratory commercial fishing operations in Cape Verde. The depth range of the area identified as fishing grounds is 300 to 950 m, whereas the depth range of the identified potential habitat is 130 to 2050 m.

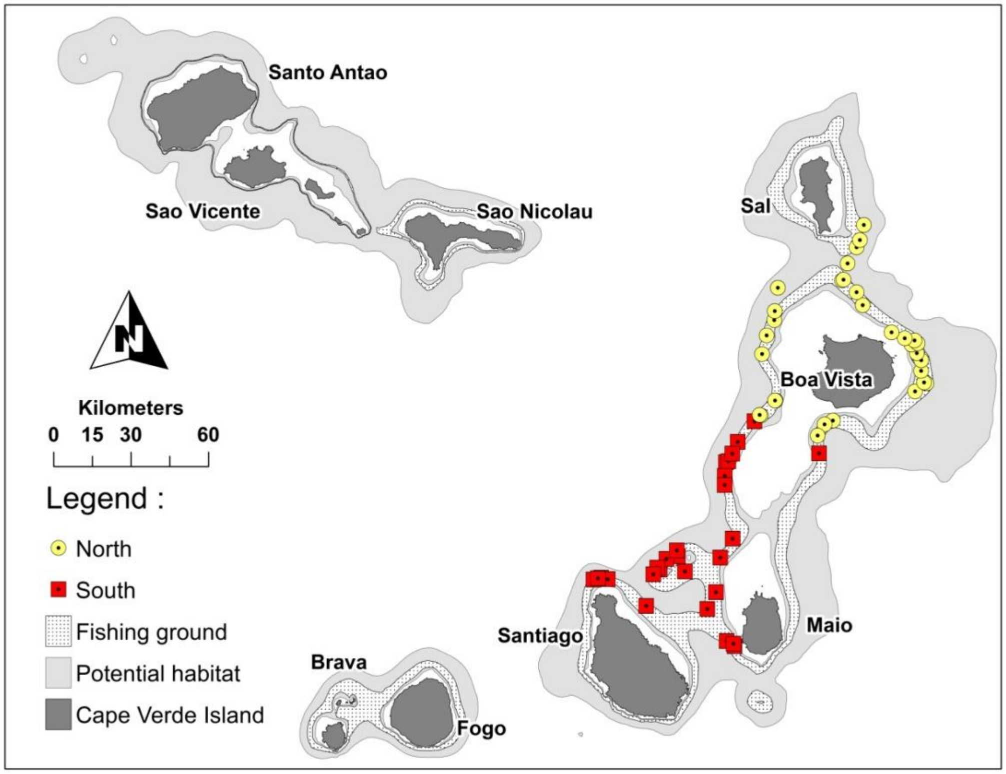


Figure 4. 2. Empirical distribution function of observed CWs during the exploratory fishing operations.

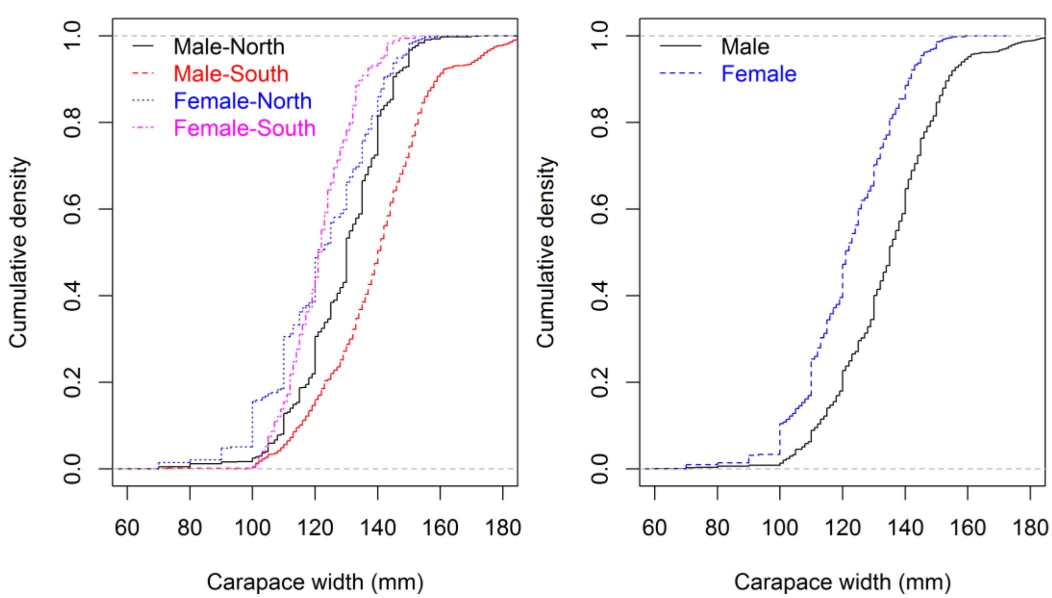


Figure 4. 3. Number of females and males red crab from exploratory fishing.

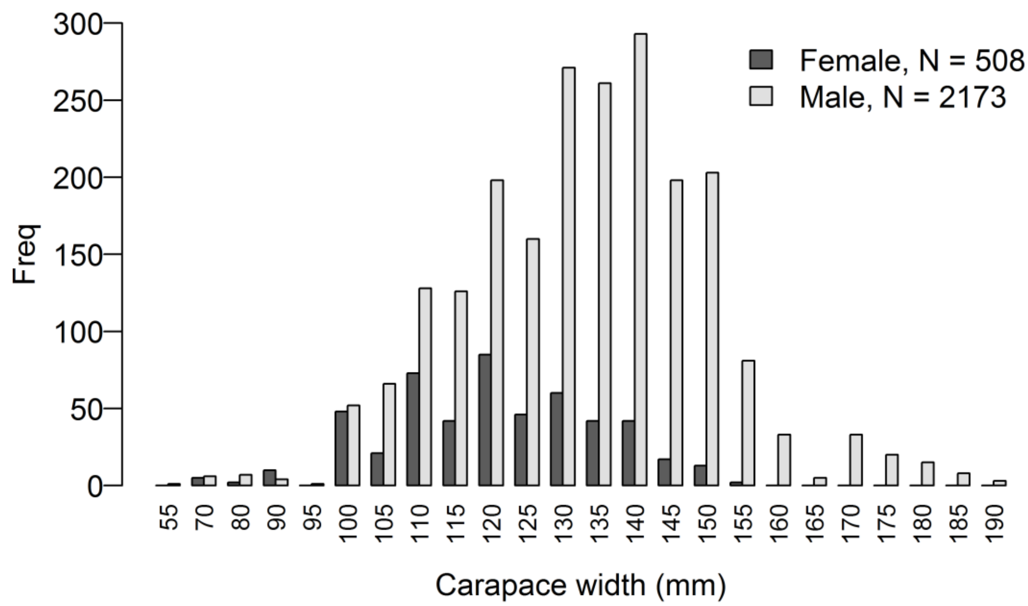


Figure 4. 4. Carapace width (CW) characteristics of male red crabs.

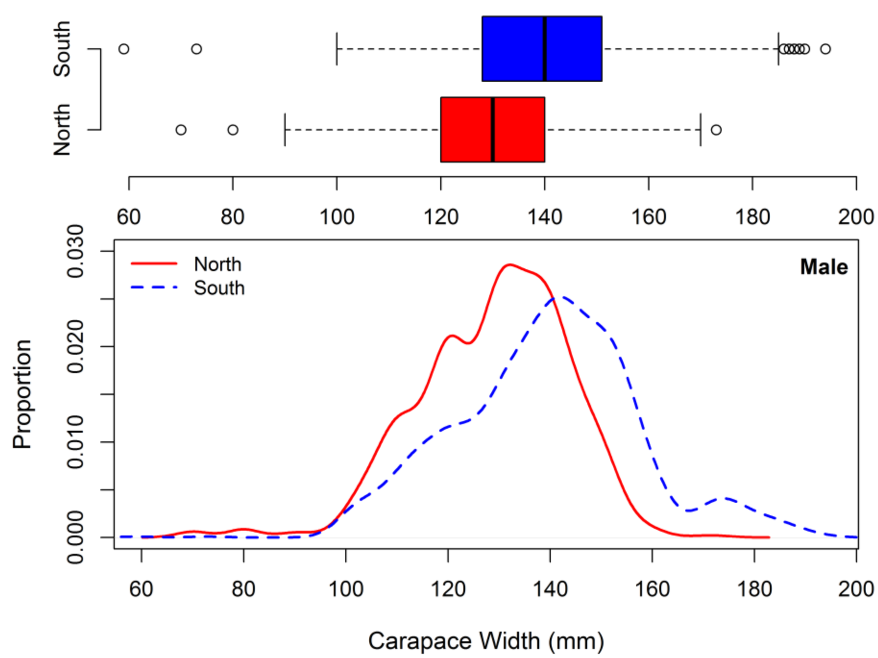


Figure 4. 5. Carapace width characteristics of female red crab.

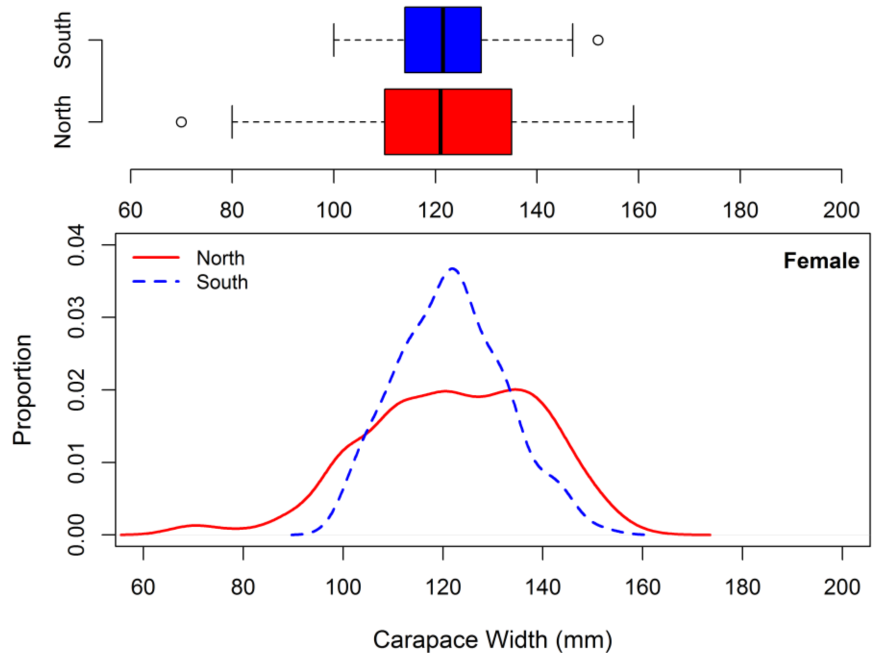


Figure 4. 6. Observations of females with and without eggs.

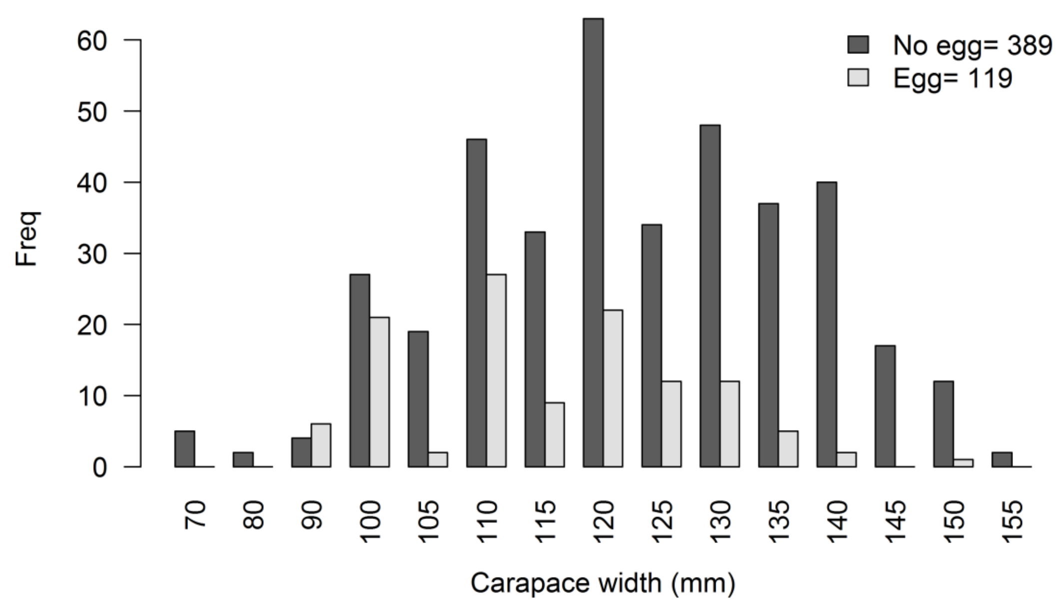


Figure 4. 7. Catch per unit effort (CPUE) for north and south area.

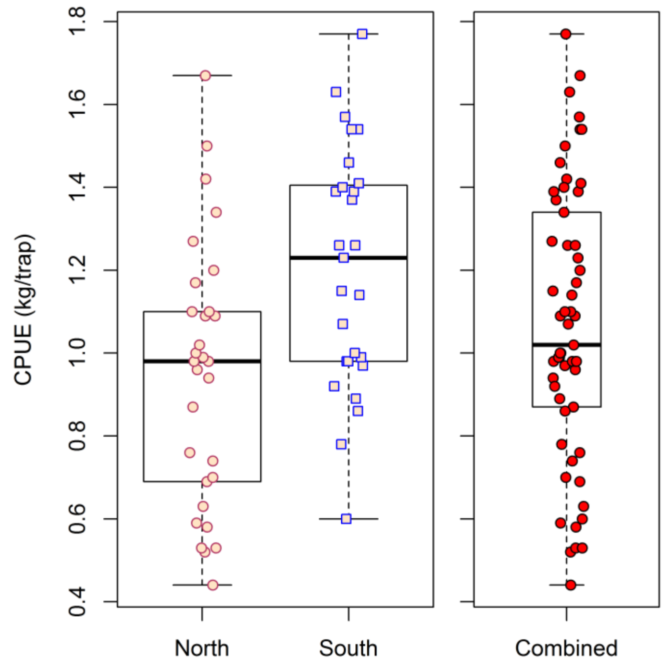
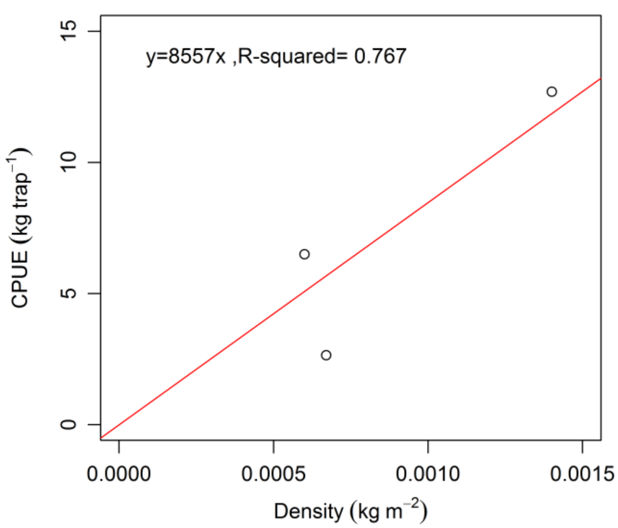


Figure 4. 8. Regression from The US and Namibian fishery.



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